The Economics of Metrology and Measurement

Report for
National Measurement Office,
Department for Business, Innovation and Skills

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Executive Summary

This report gives an overview of the economics of metrology and measurement, and government policy towards these activities. The report makes a distinction between metrology (the science of measurement), the construction of measurement tools, and everyday measurement activities.

The report addresses four main questions. Why are metrology and measurement economically important? Do we need to have a policy for metrology and measurement, and if so, why? Where do we have to intervene, and where can we trust the market? And how do we establish priorities for policy?

The report shows that metrology and measurement are important for their contribution to productivity growth, and that this can come through the use of interchangeable parts, the use of measurement in process control, and the role of measurement in improving decision-making and in reducing the regulatory burden. Metrology and measurement are important in supporting innovation, whether by improving the effectiveness of the R&D process or by making it easier for the innovative producer to market innovative new products to sceptical customers. Metrology and measurement are also important in helping to reduce transaction costs and in limiting market failure. Moreover, the report stresses that the beneficiaries of improved measurement are not just companies but include consumers, health care professionals, environmentalists, as well as teachers and their students.

The report summarises the leading arguments for having a policy towards metrology and measurement. Metrology projects have two characteristics in particular that give them a special public good character. First, the fixed costs of each project are relatively high but the marginal costs of spreading the acquired knowledge to users is small, and moreover the applicability of the results is very generic. Second, privately-funded metrology projects are liable to have rich externalities for other potential users. The main case for policy rests on these characteristics, but there are three other reasons why it may be important to have a policy towards measurement and metrology: first, the importance of network effects to users of the measurement infrastructure; second, the need to ensure that metrology remains open to all users and is not monopolised; and third, when there is a special need for impartiality and integrity in measurements.

The report argues that intervention is most important when the ratio of fixed costs to marginal costs, as described above, is high or where externalities are important. It is argued that these conditions are most relevant to metrology projects. But intervention may also be required when network effects, openness or impartiality are of special importance. By contrast, intervention is not required when fixed costs and externalities are low – and that is the case with many day-to-day measurement activities.

The report describes two approaches to defining priorities for public funding. One ranks projects according to the externalities they create, and also the ratio of consumer to producer benefits. This approach has its attractions but is difficult and costly to apply in practice. Another approach suggests some seven criteria (based on the above arguments) which can be used to assess which projects are greatest priorities for public funding. The report reminds us that a final criterion should always be considered in setting priorities: will further advances in measurement encounter diminishing returns?

Policy Makers' Summary

1. Introduction

The main report gives an overview of the economics of metrology and measurement, and government policy towards these activities.

This *Summary for Policy Makers* attempts to provide concise answers to four main questions which are likely to be of greatest concern to policy makers:

a) Why are metrology and measurement economically important?

b) Do we need to have a policy for metrology and measurement, and if so, why?

c) Where do we have to intervene? Where can we trust the market to allocate the required resources to metrology and measurement?

d) How do we establish priorities for policy?

In addition, we shall at the end make a few observations on a final question, though a full answer to this lies well beyond the scope of the present report:

e) How important is it for government to provide resources to support metrology and measurement compared to other spending priorities?

But first, it is helpful to have a brief discussion of what activities are encompassed by the terms metrology and measurement.

2. Definitions [1]

The title of the main report refers to measurement and metrology. We reserve the word *metrology* for a subset of measurement activity: "metrology is the science of measurement". [2]

In particular, the report is concerned with three areas of activity.

- *Metrology*, including basic research on measurement, refining state-of-the-art measurement methods, and the discovery of novel reference materials.

- *Tools*, encompassing the construction of measurement tools and infrastructure to carry out measurement, including method evaluation and development, proficiency schemes and the production and certification of reference materials.

[1] For further details, see Main Report, Section 1.
[2] http://www.bipm.org/en/convention/wmd/2004/

- *Applications*, encompassing the day-to-day use of tools and techniques for real-world measurement.

The report shows that the economic and policy issues around metrology are rather different from the economic and policy issues around the other two areas.

Research is pursued mainly in the public sector - in universities and government-funded research laboratories. By contrast, the development of measurement tools and infrastructure may be located in both the public and private sectors. And the day-to-day use of tools and techniques is widely dispersed across public and private sectors - in labs, companies, many parts of the public sector, and by the individual customer at home.

From an economic perspective, the three categories are rather different. Research on metrology has very large fixed costs, but is of quite general applicability and its results can be disseminated at relatively low marginal cost. Developing new tools also has significant fixed costs, but the marginal production cost per tool is not trivial. The use of measurement for day-to-day purposes usually has the lowest degree of fixed costs, but such measurement activities are often highly specific to the user.

The policy case for public support also varies across the three categories. The case for the public support of metrology research is the strongest and is similar to the traditional argument for supporting basic research. But in general, there is much less need for public support of the development of measurement tools and little or no need for public support of the day-to-day applications of measurement. The latter can *usually* be left to the market – with one notable exception, noted in the next paragraph.

In a market economy, measurement activities are located in two different places. First, each organisation in a market economy makes measurements for its own internal purposes and to ensure that it meets regulations. Like any other investment, it is usually the organisation's own business to ensure that it spends the appropriate amounts on the relevant measurement activities. Second, measurement is part of the exchange between organisations in a market economy. Here, there may be a need for policy intervention because of a possible mismatch between the measurements that the supplier is willing to supply, and the measurements that the customer would like. We return to this point in Section 4 of this summary.

3. Why is measurement economically important? [3]

Much of the main report discusses the analysis of the economic effects of measurement. In brief, there are four main areas in which measurement has important economic effects, even in the short term.

(a) First, the use of measurement can increase the productivity of organisations. This was first seen in the eighteenths and nineteenth centuries with the development of interchangeable parts; this became an important aspect of the so-called *American System* of manufacturing. The use of precise measurement revolutionised interchangeable

[3] For further details, see Main Report, Parts I and (especially) II.

manufacture because it enabled an effective and efficient division of labour. Later, measurement became one of the integral parts of process control and continues to be integral to advanced manufacturing. The more precise is the measurement and the more rapid is the feedback from measurement to control, the greater are the effects on efficiency, quality and productivity.

There are some other indirect channels by which measurement can enhance productivity. Improved measurement can support better decision making in organisations, with fewer errors in decision making, less waste and therefore greater productivity. Moreover, improved measurement can help to reduce the burden of regulation.

(b) Second, measurement supports innovation. It can do this in a variety of ways. The main report describes the example of how the Wright brothers used measurement as part of their research into the aerodynamics of aircraft wings and, building on that, as part of their development effort to build the first viable aeroplane. The main report also cites more modern examples of how publicly funded metrology activities have helped to support innovation by Rolls Royce and Boeing. These examples all illustrate a *virtuous circle* in which measurement supports R&D and innovation.

Measurement is also important to the innovator as it offers an objective way to demonstrate to customers that an innovative product is indeed superior to the competition. In the absence of any such measurements, the sceptical customer may be unconvinced, but if the superior product characteristics can be measured in an objective (and independently verifiable) way, then this supports the marketing effort of the innovative producer. In this way, measurement can play an important role in avoiding market failure for innovative new products. Another related example is the use of measurement to demonstrate the purity and quality of premium products. And the intimate relationship between measurement and innovation is illustrated in the main report by a case study of a company[4] which needed to develop its own measurement instruments in order to demonstrate the superiority of its products, and this was the first step in the diversification of the company from optical manufacture into instrumentation for advanced metrology.

(c) Third, improvements in measurement can help to reduce the transaction costs between suppliers and customers in a market economy. One of the most common sources of market failure is asymmetric information between buyers and sellers, where the buyer cannot distinguish good products from bad and therefore does not buy. Often this arises because measurement is difficult or expensive. As measurement improves and becomes cheaper, then buyers can measure any product characteristics they wish to, and that eliminates the asymmetric information and reduces the transaction costs. Indeed, many producers use measurements of product characteristics to advertise their products. Moreover, the danger of asymmetric information is not just that there will be market failure. Another possibility is that buyers will underestimate the risk of purchasing a bad product and will buy when they should not do so.

(d) Fourth, measurement can help a broader group of beneficiaries than those considered so far. For example, many consumers are interested in careful measurement of product characteristics to ensure quality, safety, purity, dosage accuracy and so on. The main

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[4] For further details, see Main Report, Section 7.4

report cites many examples including food composition data, the alcohol content of drinks, the sun protection factors of sun-block, the speed of a car and the temperature of its cooling system, the performance characteristics of hi-fi, and the accurate and early detection of carbon monoxide in the home.

In the health service, clinicians depend on the precise measurement of doses, which is essential for efficacy and safety in medicines and for the diagnosis of medical conditions. They also make extensive use of measurement instruments to check patient health (blood pressure, blood tests, and so on). Such measurements are not only important in managing the health care of individual patients, but are also important in the context of epidemics.

Those concerned with the environment depend on measurement for accurate information about meteorological conditions (wind, rainfall, sunshine, temperature, etc.), pollution and emissions (including carbon dioxide emissions), geo-seismic measures, measures of the ozone layer, measures of the condition of the polar caps, and so on. And measurement has at least three important roles in education and training: as part of the curriculum, as an essential input to the research process, and in assessing student aptitude and performance.

These four categories cover the main economic effects of measurement visible in the short term. Economic historians have also identified some longer term implications of measurement. One ambitious thesis argues that the evolution of modern capitalism was dependent on the prior development of various aspects of measurement including accounting, exact measurement of time, land surveying, weights and measures and city plans. Another such thesis asserts that the development of the modern factory system during the industrial revolution could not have been achieved without the development of accurate and affordable clocks.

In addition, there are a small number of important macroeconomic studies that have estimated a headline figure for the effects of measurement expenditures on the macro-economy. Some of this research has been commissioned in a sister project to the present report, and the reader is also referred to that.

4. Do we need to have a policy, and why? [5]

A widely held view is public policy is needed to support some parts of the measurement system - metrology in particular. Measurement is treated as one of the *infratechnologies* – the technologies that provide the infrastructure for further innovation. Equally, Measurement can also be considered a *general purpose technology*: that is, a technology which will be very widely used, and used for many different uses, and which also has much scope for improvement. Economists recognise three particular properties of infratechnologies. First, they are subject to important economies of scale and scope. Second, they are public goods. And third, the private sector left to its own devices would tend to under-invest in infratechnologies, so that government support and co-ordination is required. Moreover, we could add to this list one further feature of infratechnologies that economists often overlook: it is exceptionally hard to measure their full contribution to an economy.

[5] For further details, see Main Report, Section 11 (and also Section 5).

Why is there a tendency towards under-investment? There are two main arguments, which are inter-related. The first argument concerns economies of scale and scope. Research on a particular metrology project involves high fixed costs but the outputs of that project may have quite general applicability for a wide and diverse group of users. The fixed costs may exceed what any one user judges it worthwhile to pay. But the total benefits of the project, added up across all the diverse potential users would justify the fixed cost. It is for this reason that economists argue there is a tendency to under-investment. The total social benefit exceeds cost, but the project is not privately profitable for individual companies or small consortia.

Sometimes it may be possible to form a club or consortium of beneficiaries to share the cost between them. But often the pool of beneficiaries is so diffuse and diverse that it has to be left to a public agency to coordinate and fund the project. And, even if several individual companies and/or small consortia could afford to finance the project for their own benefit, it is uneconomical to duplicate the project in this way. For metrology projects typically have high fixed costs and low marginal costs of disseminating the results to additional users. It is most efficient to fund the project once and coordinate the diffusion of results across all potential beneficiaries.

The second argument is closely related, but couches the argument in terms of externalities. When a single company funds a metrology project itself – and many do - some of the benefits are internal to that company, but there are many potential benefits external to that company. Whenever there are positive externalities of this sort, social benefit exceeds private benefit, sometimes by a very large margin. When that margin is very wide, it is quite possible that a socially valuable project will never seem privately profitable because the externalities cannot be internalised. In this case, private funding will usually entail under-investment.

This argument is most relevant to metrology research projects, because fixed costs are high and the results are of general applicability. As a result, externalities can be very widespread and the margin between social and private benefits may be very wide. Hence, the risk of under-investment is a significant one, and there is an important role for industrial policy.

The argument is least relevant to the day-to-day uses of measurement, because in this case fixed costs are typically lower and the value of the measurement activity is much more specific to an individual user. In this case, externalities are much more limited and the margin between social and private benefits will be pretty narrow. Hence, the risk of under-investment is very small, and there is little need for industrial policy.

There are, however, three other reasons why it may be desirable to have a policy towards metrology and measurement. First, in some cases, the value of the measurement infrastructure to an individual user is greatest when as many others as possible also use the infrastructure. This is similar to the idea that the value of the internet to an individual user increases as others also use it. Economists use the term 'network effects' to describe this phenomenon: the value of the infrastructure is greatest when the number of users is as large as possible. In this case, there is an additional role for industrial policy to disseminate the benefits of measurement and encourage as many users as possible.

Second, it is sometimes essential that all of the measurement infrastructure should be *open* and that the ability to make specific types of measurements should not be monopolised by a single company or group of companies. This is relevant in the case noted in Section 2 above, where there is a mismatch between the measurements offered by a supplier and the measurements wanted by a customer. This can happen where a supplier's product does not score well on a particular product characteristic and the seller does not particularly wish to draw attention to this fact. If the ability to measure that characteristic is monopolised by this supplier, then the customer will not be able to correct this mismatch. To avoid such cases, it is highly desirable that the measurement infrastructure should always be open and this may call for public funding of metrology to avoid any monopolisation.

Third, and related, there is a long historical tradition that weights and measures should be defined by the monarch or the state, to ensure impartiality and integrity. There has long been a concern that if weights and measures are defined by interested parties on the supply (or demand) side, then this impartiality and integrity may be lost, and that will exacerbate the problems of transaction costs and market failure which accurate measurement is supposed to resolve. This argument is perhaps most relevant to legal metrology, but also to any area where traceability is essential.

A final observation should be made here. It is likely that the role of NMS in supporting innovation in a particular industry will vary over the industry life-cycle. When the industry is in its formative stages, a wide variety of NMS activities may be important. But when the industry is mature, the role of the NMS may be limited to providing reference materials.

5. Where do we have to intervene, and where can we trust the market? [6]

In which areas of measurement is a policy required, and in which can decisions be left to the market? The general guidelines follow the principles of Section 4 above. A policy intervention is most important in those cases where the risk of under-investment is greatest, or when the other three factors noted above (network effects, open-ness and impartiality) are especially important. But in those cases where that risk looks small (and the three other factors are not important), then there is little need for policy.

The risk of under-investment is greatest under the following conditions:

- (i) The ratio of the fixed costs to the marginal costs (for a project) is large
- (ii) The applicability of results from a project are highly generic
- (iii) The benefits from a project are very diffuse (across many sectors and types of beneficiary)
- (iv) The benefits are hard to internalise within a club or consortium

These conditions are inter-related. If applicability is generic then potential benefits are spread over many sectors and beneficiaries and that, in turn, makes internalisation more difficult. And, in turn, these conditions define the cases in which policy intervention is most relevant. In general, it is fair to conclude that the most important area for policy is in metrology research, while there is less need for policy towards the construction of

[6] For further details, see Main Report, Section 11 (and also Section 5).

measurement tools, and little or no need for policy towards day-to-day measurement. Moreover, these four conditions can be interpreted as four different features of projects that are *rich in externalities*.

Turning to the other three factors listed above, we can draw some very rough conclusions about the circumstances in which policy interventions are most relevant.

Network effects are typically of two types. *Direct* network effects arise when network members benefit directly from the inclusion of *specific* other members in the network. *Indirect* network effects arise when network members benefit from the supporting products and services that tend to cluster around a well-used network. Direct network effects can sometimes grow without limit as the network expands, while indirect network effects tend to reach an upper limit. This suggests that policy interventions are most relevant where network effects are direct rather than indirect.

Open-ness is probably most important in the case of 'problem' product characteristics – such as potentially toxic characteristics, or characteristics where products have a history of poor performance. These are the cases where monopolisation of metrology would be most undesirable, as customers would be denied essential measurements. Finally, impartiality and integrity are probably most important for measurements that are predominantly used for trading between organisations in a market economy, rather than for the internal benefit of an organisation.

6. How do we establish priorities for policy? [7]

As noted before, it is fair to generalise that the top priorities for public funding would be those aspects of metrology and measurement that show the greatest 'public good' character. This argument is strongest for metrology research, but weaker for the development of measurement tools and very weak for day-to-day use of measurement.

But going beyond this broad recommendation, how do we establish specific priorities amongst projects? Which areas of metrology research are most in need of public funding?

One approach to answering this question, described in the main report, identifies some 19 different mechanisms through which metrology projects may impact on the economy. In this approach, metrology professionals are invited to indicate which mechanisms they think are most relevant to each particular project under consideration. When this is done, a model can be used to split the benefits from the project into three broad categories:

- Producer benefits
- Consumer benefits
- Externalities

According to this approach, the top priorities for receiving public support are those where the share of the benefits accruing as externalities is greatest. If two projects each generate an equal share of externalities, then the greater priority will be the one for which the share

[7] For further details, see Main Report, Section 12 (and also Section 10).

of consumer benefits is greatest. The rationale for this method of ranking is that externalities are the hardest form of benefit to internalise while producer benefits are the easiest form of benefit to internalise (in a consortium or club). Accordingly, the priorities for public funding are those where internalisation of benefits is hardest.

While this approach has some attractions, it is difficult and costly to apply in practice. Studies by NIST in the USA have shown that while it is possible to measure the benefits and externalities from measurement, it is costly to do so. That is true for historic projects where the benefits and externalities have already occurred. It is much harder to make such estimates when the projects have not yet taken place and accordingly the benefits and externalities all lie in the future. The main objection to this method is that it requires a level of investment in assessing the economic benefits of putative projects above that which the NMS is prepared to make at present.

An alternative to this externalities-centred approach is a criteria-driven approach. This would rank projects using a qualitative assessment of the criteria listed in Section 5 above. Priorities for public funding would be those projects for which:

- (i) The ratio of the fixed costs to the marginal costs (for a project) is large
- (ii) The applicability of results from a project are highly generic
- (iii) The benefits from a project are very diffuse (across many sectors and types of beneficiary)
- (iv) The benefits are hard to internalise within a club or consortium
- (v) The network effects around the measurement infrastructure are greatest
- (vi) The risks from closed measurement are greatest
- (vii) The impartiality and integrity of measurements is of prime importance

As noted, before, however, this criteria-driven approach is really just a different way of looking at externalities: the first four conditions can be interpreted as four different features of projects that are *rich in externalities*.

Finally, there is one other factor that needs to be born in mind when assessing priorities. The main report shows that there may be an s-shaped relationship between the accuracy of measurement and the economic returns from measurement accuracy. Unless measurement accuracy reaches a certain level, it is hard to generate economic benefits. Then, when a *critical level* of accuracy is reached, there are rapidly increasing returns to measurement accuracy. The main report shows a number of examples (Sections 7.3 and 10.1) where there may be such a *critical mass*. Then, beyond that point, there may be diminishing returns to greater accuracy. In some cases, however, if increases in the accuracy of measurement are matched by increases in knowledge of what to do with the technological potential thus created, then there can be ongoing positive returns to greater measurement accuracy.

These last observations suggest two policy considerations. First, if there is a critical mass effect, then any policy intervention needs to reach this critical level, or it is barely worth doing. Second, those projects where benefits from greater measurement accuracy are ongoing will, other things equal, be greater priorities for public support than those for which these benefits are diminishing.

7. How important is metrology compared to other spending priorities?

A full answer to this final question lies well beyond the scope of this report. For it would involve an assessment of how every other publicly funded activity compares with metrology on the seven criteria listed in the last section:

(i) The ratio of the fixed costs to the marginal costs (for a project) is large
(ii) The applicability of results from a project are highly generic
(iii) The benefits from a project are very diffuse (across many sectors and types of beneficiary)
(iv) The benefits are hard to internalise within a club or consortium
(v) The network effects around the activity are great
(vi) The risks from 'closed' activity are great
(vii) The impartiality and integrity of the activity is of prime importance

To do that would involve a substantial programme of research spread over all areas of policy, which would be a very large task.

However, we can draw some preliminary conclusions as to how well metrology and measurement scores on these seven criteria. Referring to criterion (i), it seems clear that much metrology activity involves very substantial fixed costs, while the marginal cost of spreading the benefits of that activity to multiple users is low. Referring to criterion (ii), some metrology activity generates benefits that are highly generic. That in turn means that benefits are diffuse (criterion iii) and may be hard to internalise as the interested consortium or club will be very large (criterion iv). The main report discusses the idea that a measurement activity is more important the more numerous are the users of that technique (criterion v). It also discusses the risks of 'closed' measurement (criterion vi) and the need for impartiality and integrity (criterion vii).

In short, metrology is an activity that scores well on the above criteria, indicating that it is an activity requiring public support.

The Main Report

Introduction

The objective set for this short project was to provide an overview of the economics of metrology. This report will provide an economic analysis of the role of the National Measurement System and, in particular, the economic rationale for public funding of the scientific research in metrology that underpins it.

The report will draw on the earlier report for the 1999 review of the NMS (Swann, 1999). The 1999 report took a very broad perspective on the economics of measurement. This new report will look at specific aspects of the economics of measurement in more detail. It will take account of a wider range of sources of ideas and evidence, including some new thinking and neglected insights from some classic works.

The structure of this preliminary draft is as follows. The first part provides a context for this study by describing what measurement does in economic terms, reviewing what some of the classics of economics have to say about measurement, and observing that some of the issues addressed here also crop up in other parts of the economics literature. The second part provides a brief survey of some of the main elements of the literature on the economics of measurement, focussing in particular on the effects of measurement on productivity, innovation and transaction costs – as well as other stages in wealth-creation. The third part describes the case for governments having an active policy towards measurement and makes some observations on how policy priorities can be identified.

Where is it all leading?

In a thoughtful paper, Sydenham (2003, p. 3) observes that a lot of time and money has gone into the science and art of measurement and it is natural to ask: "why we make measurements" and "where is all of this leading?" Sydenham concludes that few workers in the metrology and measurement profession are addressing these issues. (The same could be said of the economics profession.) He observes (2003, p. 4): "many measurement researchers conduct their critical thinking in relative isolation of the holistic world in which their contributions sit." Sydenham is concerned with four main questions (2003, p. 4):

(1) What is the purpose of measurement?
(2) How does measurement advance the state of human existence?
(3) What is known about the relationship between measurement and advancement?
(4) Where might it all be heading in the future?

These questions are very good ones but broader than the scope of this report, which is concerned with the economic implications of measurement. Nonetheless, this report will concern itself with narrower versions of the first three questions, which we recast as:

(1*) What is the economic purpose of measurement?
(2*) How does measurement advance the state of the economy?
(3*) What is known about the relationship of measurement and economic advance?

And we shall make a few observations on question (4) in Section 10.

Part I: Context

1. The Locus of Measurement

2. Classic Literature

3. Some Examples: Modern and Historical

4. Adjacent Literatures within Industrial Economics

1. The Locus of Measurement

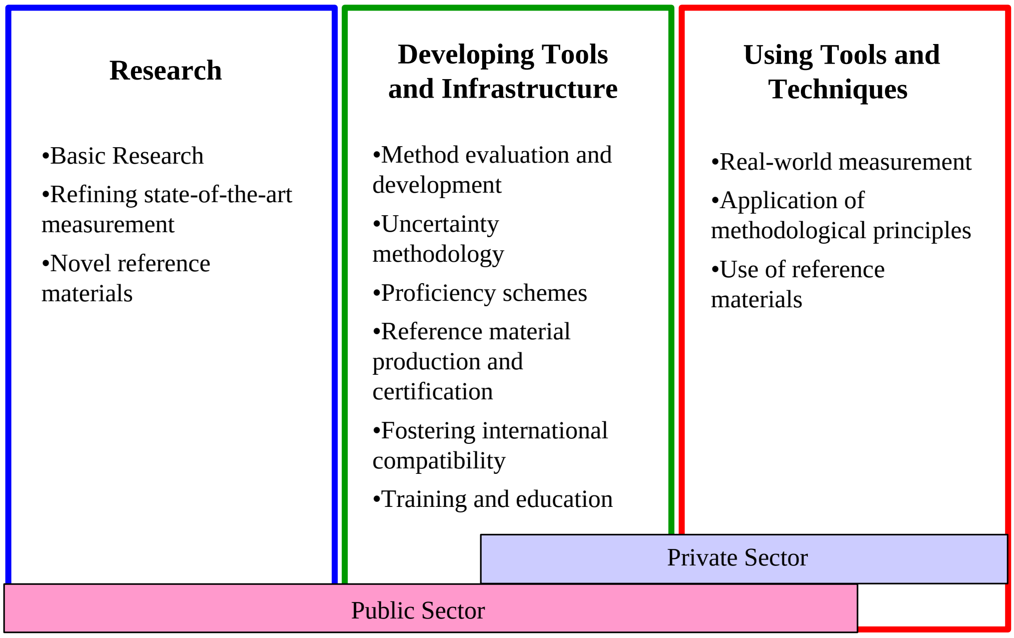
What is measurement? And what position does it have in the economy? Readers from the NMO surely do not need to be told the answer to the first question. But they may be less clear about the answer to the second question. Moreover, as some of the readers of this report may have no specialist knowledge of the National Measurement System, then the answer to the first question will be of use to them too.

Our aim here is to describe measurement activities in a way that brings out their economic significance. In what follows we map measurement activities in two ways. One could be called a functional and sectoral map: what sorts of measurement activity are there, and where do they take place? The second maps the economic role of measurement activities by locating them within a simple model of a market economy.

1.1 A Functional and Sectoral Map of Measurement Activity

It is helpful to distinguish three rather different categories of measurement activity, and note that some of these take place in the private sector and some in the public sector. There is research in measurement: basic research, refining state of the art measurement and discovery of novel reference materials. There is the development of measurement tools and infrastructure to carry out measurement, including: method evaluation and development, proficiency schemes and the production and certification of reference materials. And third, there is the day-to-day use of tools and techniques for real-world measurement. Figure 1 gives a more detailed indication of what each category comprises.

Figure 1
Categories of Measurement Activity



Source: Swann (1999)

Research is pursued mainly in the public sector - in Universities and Government funded research labs. By contrast, the development of measurement tools and infrastructure may be located in both public and private sectors. And the day-to-day use of tools and techniques is again located in both public and private sectors - in large public labs, but also in labs within large companies, small specialist analytical labs, and even by the individual at home (home self-test medical kits, for example).

From an economic perspective the three columns represent rather different sorts of activity. They are differentiated in terms of their cost functions - see Figure 2 (overleaf). Research has large fixed costs, but its results can be disseminated (at least in some form) quite widely at relatively low marginal cost. Developing new tools also has significant fixed costs, and economies of scale, but the marginal production cost per tool is not trivial. The use of measurement for day to day purposes has probably the lowest degree of economies of scale. These activities are also differentiated in terms of their generality or specificity, basic research having the greatest generality, and measurement activities relevant to a particular operation having the greatest specificity.

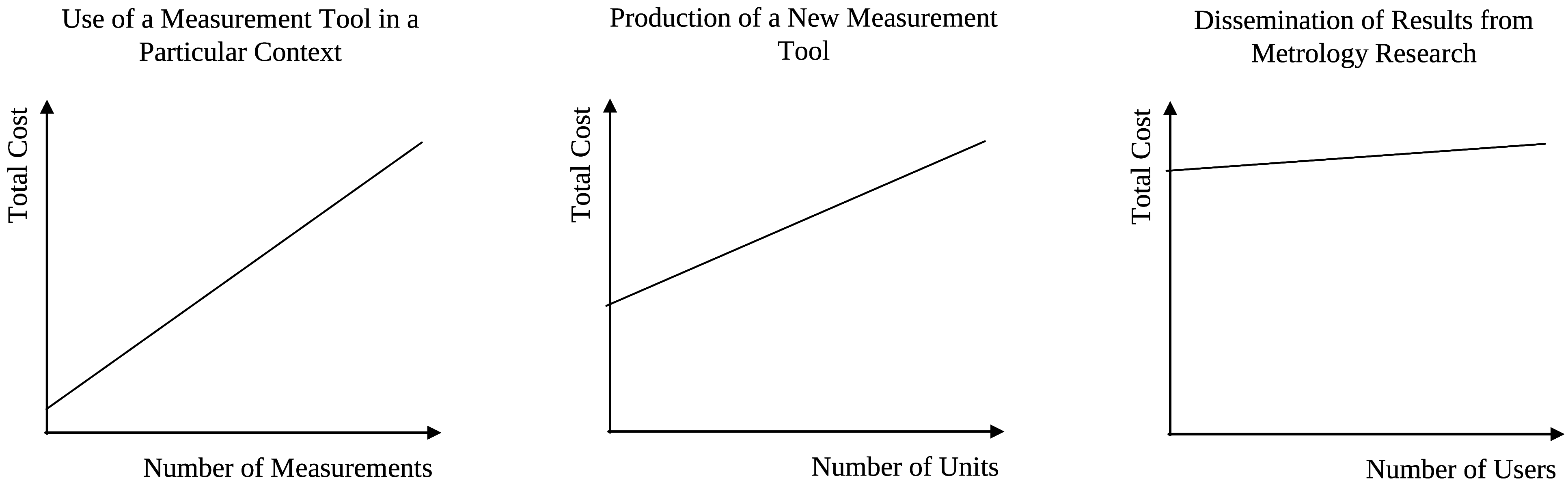
Moreover the rationale for investing in each of the three stages is very different. In making a business case to company management as to why they should invest more of their own funds in *using* measurement within their company, the case would ultimately have to address the *bottom line*. Does this investment deliver sufficient benefits in terms of increased sales, market share, or increased profit to justify the cost? Some companies would have a fairly good ‘gut feel’ for the answer to this, but the basic economics of private R&D could be used to analyse the benefits of such an investment. If there is a case to be made, it will rest on the argument that private investment will yield benefits to the firm in excess of the costs they incur.

Of course, some investment in measurement is undertaken not so much with an eye on profitability, but as a necessary pre-requisite to being in business at all. If a chemical company’s analysis does not serve to convince the regulatory authorities worldwide that its products are safe, efficacious and quality-controlled, the company will not be able to trade.

This first case, however, would be different from the case to be made to government for public investment in measurement activity. The latter case should not simply rest on demonstrating that this investment will yield a benefit to business or customers in excess of the cost to the public purse. For then the obvious retort is: “Why does this activity need to receive *public* funding? Why doesn’t the private sector fund this?” Instead, the typical economic case for industrial policy rests on the market failure argument. We turn to that in Part III of the report.

The case for public investment in measurement will also vary according to which category of measurement activity is being discussed. The case for the support of research in measurement is likely to be similar to the traditional argument for supporting basic research in general. This will be discussed in Part III of the report. When we move nearer to the market, these arguments often lose force.

Figure 2
Cost Functions for Different Measurement Activities

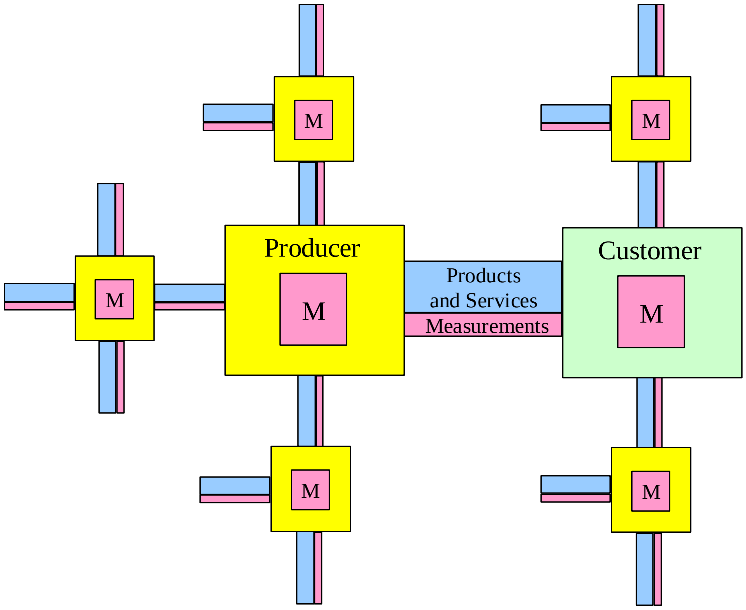


Source: Swann (1999)

1.2 An Economic Map of Measurement Activity

The first map describes measurement activities and where they are located, but it does not give a clear picture of where measurement fits into the broader framework of a market economy. Figure 3 describes a simple economic map of measurement activity. We shall see in section 1.3 that it is really too simple in that it focuses only on producers and customers and these are not the only users of measurement. However, it is a good place to start.

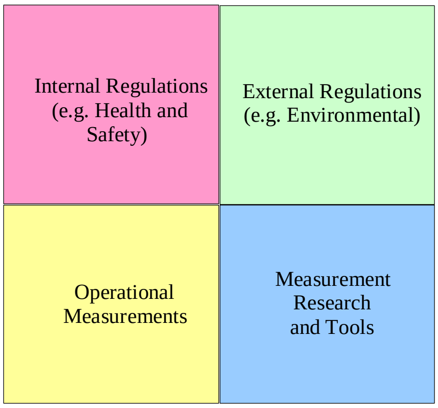
Figure 3
Locus of Some Measurement Activities



Source: Swann (1999)

Measurement is located here in two places. First, it is located inside each organisation, where it is represented as a smaller box inside the producer or customer boxes. And second, it is part of the exchange between organisations, alongside traded goods and services. We shall argue that the economic conditions governing these two differently located measurement activities are rather different. We can open up the measurement box within each organisation, and this is what we find (Figure 4, overleaf).

Figure 4
Measurement inside the Organisation



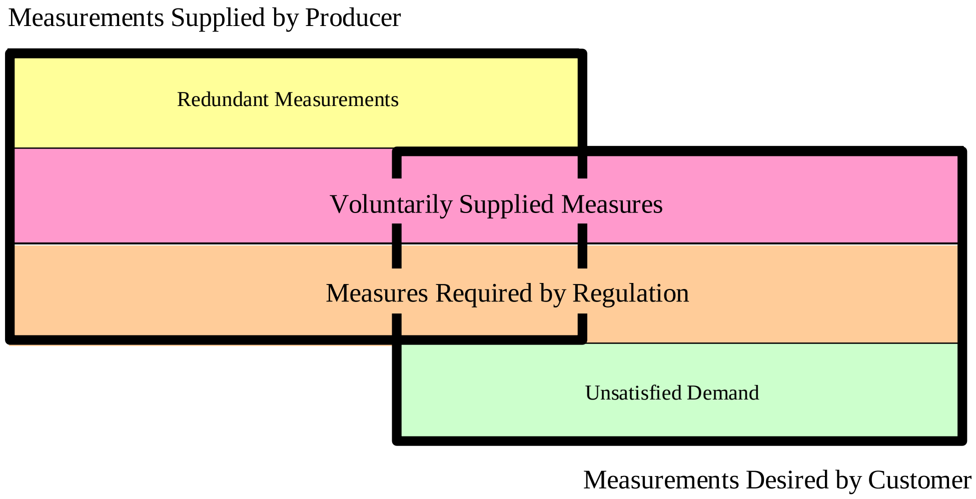
Source: Swann (1999)

Here there are mandatory measurement activities, to conform with those regulations that govern operations within the company (e.g. health and safety regulations) and also with those regulations that govern the effects of operations on the outside world (e.g. environmental regulations). There are operational measurements as part of the production process, and there may be activities directed towards improving measurement tools, and perhaps even some research.

Clearly, all of these are important to the company's success. But rather like any other investment, we could argue that it is the company's own business to spend the appropriate amounts on the relevant measurement activities. If it does not, it may not meet health and safety regulations, environmental regulations, or it may simply put itself at a competitive disadvantage.

Now when we open up the measurement channel between organisations, Figure 5 shows what we find. It shows a Venn diagram, with a set of measurements supplied by the producer and a set of measurements desired by the customer. For reasons that will become clearer in Part III, these may not overlap perfectly. There may be some measurements quoted by the supplier that are - from the customer's point of view - unimportant or even redundant. But more important, there may be some measurements that the customer would like but which the producer either cannot or will not supply. Why should that be? We explore this in more detail in Part III, but the basic idea is that producers do not generally have much incentive to publish measurements that show their product or service in a poor light.

Figure 5
Measurements: The Producer and the Customer



Source: Swann (1999)

Some of the overlap will be measurements that the producer is obliged to publish in order to satisfy trading regulations. Some by contrast will be measures that the producer is not obliged to publish, but is happy to do so. But this model also illustrates how the degree of standardisation of these measurements may be very important. If the customer is processing measurement data from a variety of sources, or if he wishes to preserve an option to switch suppliers frequently, then standardisation of measurement is highly desirable.

This observation has led some (including the present author) to argue that the economics of measurement has much in common with the economics of standards. Perhaps it would be more accurate to say that *some* aspects of the economics of measurement are *very similar* to the economics of standards - while others are *not*. Those measurement activities that are done to ensure that production processes or products and services meet regulatory requirements, and those that are done to enable trade between suppliers and customers certainly have a great deal in common with the economics of standards. On the other hand, those measurement activities that are done for internal operational purposes have a rather different economic character. When we focus on the business case for operational measurement, this may be directed at increasing the efficiency of production, for example. Here, a useful analogy is with the *economics of investment* in cost reducing process innovations.

And finally, as noted already, those measurement activities directed at developing new tools and techniques and at metrology research have a quite different character again. Some of these are be akin to R&D activities (reverse engineering and synthesising new materials, for example) - and hence some aspects of the *economics of R&D* are relevant.

1.3 Other Measurement Activities

As we said at the start of Section 1.2 however, the model there is too simple. It concentrates on the use of measures by producers and customers, but there are other users.

Figure 6
A Wider Map of Wealth Creation

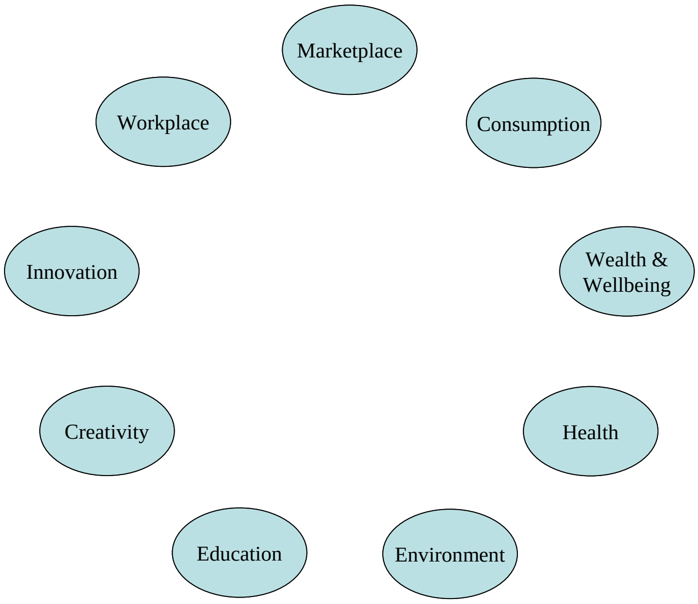


Figure 6 gives a much broader perspective on some of the activities that contribute to wealth creation. The most commonly discussed linkages run from innovation through the workplace and the marketplace to consumption and then wealth creation. However, even if that is the most important *economic* route to creating wealth and wellbeing – and some would dispute that - it is nonetheless by no means the *only* route.

Three examples illustrate the general point. First, health is one of the most important factors in wealth and wellbeing. It is influenced positively and negatively by several of the economic factors in the top half of Figure 6, but by many other factors as well. This suggests a direct link from health to wealth creation. Second, for many people, living in a good environment is an essential factor in their wealth and well-being; and for many others, living in a congested, noisy and polluted environment does great damage to their well-being. This suggests either a direct link from environment to wealth creation, or an indirect link via health. Third, many who work in education believe that the value of education is not limited to creating a well trained and employable workforce. For sure that is important, but it is not the only way in which education contributes to wealth creation. Education can make us better and wiser consumers, it can help to keep us healthy, and can teach us how to channel creativity towards wealth creation. This suggests linkages from education to wealth creation which do not pass through the workplace, the marketplace and consumption.

Indeed, these three are not the only additional linkages at work. Some would argue that there may indeed be linkages between every pair of elements in Figure 6. That is debateable, but there are certainly quite a lot. As we shall see in Section 9, measurement probably has a role in many if not most of those linkages.

2. Classic Literature

In this section, we shall give a brief account of the role of measurement in some of the great classic works of economics. The non-economist reading this section may wonder why economists still refer to classical works: surely the subject has progressed since the time of Adam Smith (1776)? Or as Boulding (1971) put it with characteristic irony: "after Samuelson,[8] who needs Adam Smith?"

One of the main reasons why we still consult the works of classic economists is that they achieved an intellectual breadth within economics (and beyond) that is hard to achieve today, given the intellectual division of labour of our age. Adam Smith saw and wrote about a large number of interconnections across the whole field of the social sciences. Today, by contrast, each of these topics is located in special sub-sub-disciplines of our subject. The modern economist (like the modern scientist) is usually a narrow specialist in one sub-sub-discipline,[9] and it is rare for him/her to have an appreciation of the big picture in the same way as these classic economists.

2.1 Mediæval Economic Thought

In her survey of mediæval economic thought, Wood (2002) devotes one whole chapter (out of a total of eight chapters) to weights and measures, including coinage.[10] As she argues, integrity of metrological standards and coinage were considered to be of vital importance to the smooth operation of an economy and those who tampered with weights and measures or debased the coinage were considered to have committed severe offences. How different that is from modern economic textbooks where, apart from the measurement of economic phenomena, the topic of weights and measures attracts no attention at all, and measurement (like standards) is one of those topics that are taken for granted.

Wood (2002, Ch. 8) argues that the very concept of weighing and measuring was fundamental to Christianity, Judaism and Islam. All three laid great stress on the need for integrity in metrological standards. And the idea that standards were, in a sense, 'divine' was reflected in the fact that standard weights and measures were kept in holy places. Mediæval economic thought reflected many passages from the Old Testament:

> "Just balances, just weights, a just ephah,[11] and a just hin,[12] shall ye have." (Leviticus 19:36)
>
> "You shall not have in your bag differing weights, a large and a small." (Deuteronomy 25:13)

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[8] Paul Samuelson (b. 1915, and winner of the 1970 Sveriges Rijksbank Prize in Economic Sciences in Memory of Alfred Nobel) was one of the pioneers of modern mathematical economics.

[9] The present author is a specialist in the economics of innovation, which is generally considered to be a sub-division of industrial economics. If industrial economics is a sub-discipline, then the economics of innovation is a sub-sub-discipline.

[10] No modern introduction to economics would devote anything like that amount of space to weights and measures. In some of the leading introductory texts, indeed, the topic is not mentioned at all.

[11] A measure of dry volume from Biblical times

[12] A measure of liquid volume from Biblical times

> "Differing weights and differing measures, both of them are abominable to the Lord." (Proverbs 20:10)

Traders in mediæval markets would often be reminded of these warnings. An inscription on St Giacomo di Rialto, Venice, exhorts traders as follows:[13]

> "Around this temple, let the Merchant's law be just, his weights true, and his contracts guileless"

And similar messages were found in other (strictly secular) marketplaces. For example:

> "Who seek to find eternal treasure, must use no guile in weight or measure" (Truro Market Hall, 1615) [14]

Wood (2002, Ch. 8) describes how the connection between weights and measures, on the one hand, and coinage, on the other, was a close one in the Middle Ages. Control of standards allowed a sovereign or ruler to regulate people's lives. The standard managed the boundaries of land on which they lived and worked. In the marketplace, standards controlled the amounts of essential commodities such as food, drink, and cloth. In short, weights and measures were essential to exchange just as much as money. By the end of the Middle Ages, the power of the sovereign waned and representative institutions grew to fill that place. Control of the standards passed to Parliament or other representative assemblies, and was implemented by the lord of the manor or the borough officials.

Having said that, it was one thing for a sovereign to decree that there should be common weights and measures throughout his/her realm, but quite another to enforce that. Many attempts were made but could not always be enforced and local or regional variations would persist. Nonetheless, Wood (2002, p. 96) described how:

> "The appearance of the lord's surveyor with his measuring rod was an occasion of fear and apprehension. Not only did he use the lord's measure, which might be smaller than the customary measure, but his visit might mean that a peasant had tilled over a neighbour's boundary, or, far worse, it might be the prelude to the enclosure of the land and eviction of the tenant."

2.2 Smith and After

Moving on to the writings of economists proper, from Adam Smith onwards, we find that discussion of the economic effects of measurement was without doubt more prominent than in the core economics texts of today.

There are a variety of possible reasons for this. One possible reason is simply that today we take measurement for granted as an integral and unremarkable part of the technology infrastructure, whereas, during Smith's time, measurement could not be taken for granted. So, if we want to understand what difference measurement makes to the way the world

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[13] Ruskin (1996, Volume 17, p. 20). He dates this inscription to about 1073.
[14] There is a similar inscription in the Manchester Cotton Exchange (1729)

works, then we can learn much from reading about a world in which measurement was not as advanced as it is today.

Smith

It is humbling to find that many modern ideas in economics can in fact be found, at least in an elementary form, in Adam Smith's great *Wealth of Nations* (1776). And so it is with measurement. In Book 1, Smith offered an interpretation of why the nations around the Mediterranean were the first economies to derive great benefits from marine trade (Smith, 1776/1904, Book 1, Chapter 3, p. 21):

> "The nations that …. appear to have been first civilised, were those that dwelt round the coast of the Mediterranean Sea. That sea …. was, by the smoothness of its surface, as well as by the multitude of its islands, and the proximity of its neighbouring shores, extremely favourable to the infant navigation of the world; when, from their ignorance of the compass, men were afraid to quit the view of the coast, and from the imperfection of the art of shipbuilding, to abandon themselves to the boisterous waves of the ocean."

In this account, the "ignorance of the compass" would restrain the ambition of sailors to leave sight of land. But as it was possible to navigate between ports in the Mediterranean without losing sight of land, then the growth of trade was possible before the advent of the compass. By implication, trade by the more ambitious trading routes only became possible with the advent of the compass. The example gives the compass a prominent place as a measurement instrument which reduces the risk of navigation.

We return to this example in Section 3, where we shall see that the details of Smith's arguments are not completely accurate from the perspective of maritime history. But the principle behind this – that navigation without a compass is more risky than navigation with a compass - is sound enough.

Babbage

Charles Babbage's (1835) book on the *Economy of Manufactures* was based on a great deal of empirical research. As a professor of mathematics, Babbage might have indulged in high theory, but on the contrary he went out of his way to learn a great deal of practical detail on how manufacturers went about their business. That research showed him the role which measurement played in economic affairs.

Babbage (1835, Ch. 8, Para. 65) writes of the merits of machinery for counting and registering:

> "One great advantage which we may derive from machinery is from the check which it affords against the inattention, the idleness, or the dishonesty of human agents. Few occupations are more wearisome than counting a series of repetitions of the same fact; the number of paces we walk affords a tolerably good measure of distance passed over, but the value of this is much enhanced by possessing an instrument, the pedometer, which will count for us the number of steps we have made."

Babbage (1835, Ch. 9, Para. 77) writes the value of measurement precision in economising on the use of raw material inputs:

> "The precision with which all operations by machinery are executed, and the exact similarity of the articles thus made, produce a degree of economy in the consumption of the raw material which is, in some cases, of great importance."

Babbage (1835, Ch. 10, Para. 79) writes with excitement of how precision in tools and methods allows the manufacturer to reproduce to a high standard of conformity with little extra work:

> "Nothing is more remarkable, and yet less unexpected, than the perfect identity of things manufactured by the same tool. If the top of a circular box is to be made to fit over the lower part, it may be done in the lathe by gradually advancing the tool of the sliding-rest; the proper degree of tightness between the box and its lid being found by trial. After this adjustment, if a thousand boxes are made, no additional care is required; the tool is always carried up to the stop, and each box will be equally adapted to every lid."

But perhaps the most foresighted of Babbage's observations on the importance of measurement was in his Chapter 15 where he discusses what he called the costs of *verification.* Here he anticipates the Twentieth Century concept of transaction costs. (Babbage, 1835, Ch. 15, Para. 182):

> "The cost, to the purchaser, is the price he pays for any article, added to the cost of verifying the fact of its having that degree of goodness for which he contracts. In some cases the goodness of the article is evident on mere inspection: and in those cases there is not much difference of price at different shops … on the other hand, tea, of which it is exceedingly difficult to judge, and which can be adulterated by mixture so as to deceive the skill even of a practised eye, has a great variety of different prices… the difficulty and expense of verification are, in some instances, so great, as to justify the deviation from well-established principles."

(Babbage, 1835, Ch. 15, Paras. 185 and 186) cites example in the lace and stocking trades:

> "And it is shown by the evidence, that a kind of lace called single-press was manufactured, which, although good to the eye, became nearly spoiled in washing by the slipping of the threads; that not one person in a thousand could distinguish the difference between single-press and double-press lace; and that, even workmen and manufacturers were obliged to employ a magnifying glass for that purpose …" [15]

> "In the stocking trade similar frauds have been practised. It appeared in evidence, that stockings were made of uniform width from the knee down to the ankle, and being wetted and stretched on frames at the calf, they retained

[15] Babbage goes on to show the operation of a Gresham's Law or Lemons Effect in this case, where bad practice drives good traders out of business.

> their shape when dry. but that the purchaser could not discover the fraud until, after the first washing, the stockings hung like bags about his ankles."

Sometimes, it is hard for the customer to verify quality to avoid such frauds. In other cases, verification imposes a cost on seller and buyer alike (Babbage, 1835, Ch. 15, Para. 188):

> "The practice, in retail linen-drapers' shops, of calling certain articles yard wide when the real width is perhaps, only seven-eighths or three-quarters, arose at first from fraud, which being detected, custom was pleaded in its defence: but the result is, that the vender is constantly obliged to measure the width of his goods in the customer's presence … and the purchaser, if not himself a skilful judge (which rarely happens to be the case), must pay some person, in the shape of an additional money price, who has skill to distinguish, and integrity to furnish, articles of the quality agreed on."

Marx and Mumford

Lewis Mumford was not an economist as such, yet few writers of the Twentieth century understood better than him the effects of technical change on economic and social development. One of Mumford's most important theses was that the *clock* was the most important machine of the industrial age. This thesis puts measurement at the heart of economic development (Mumford, 1934, p. 14):

> "The clock, not the steam-engine, is the key-machine of the modern industrial age. For every phase of its development the clock is both the outstanding fact and the typical symbol of the machine: even today no other machine is so ubiquitous. Here, at the very beginning of modern technics, appeared prophetically the accurate automatic machine which, only after centuries of further effort, was also to prove the final consummation of this technics in every department of industrial activity."

While some historians cannot accept that the status of the clock exceeds that of the steam engine, Mumford argued that Marx was of like mind. I quote Mumford at length here (1967, p. 286:

> "The machine that mechanized time did more than regulate the activities of the day: it synchronized human reactions, not with the rising and setting sun, but with the indicated movements of the clock's hands: so it brought exact measurement and temporal control into every activity, by setting an independent standard whereby the whole day could be laid out and subdivided.
>
> In the sixteenth century the tower clock in the late medieval market-place, which struck the hours, moved into the upper-class home on the mantel shelf, and by the nineteenth century, reduced to the size of a watch it became part of the human costume: exposed or pocketed. Punctuality, ceasing to be 'the courtesy of kings' became a necessity in daily affairs in those countries where mechanization was taking command. The measurement of space and time

> became an integral part of the system of control that Western man spread over the planet.
>
> Karl Marx was one of the first to understand the place of the clock as the archetypal model for all later machines: in a letter to Friedrich Engels in 1863 he observed that 'the clock is the first automatic machine applied to practical purposes; the whole theory of *production and regular motion* was developed through it.' The italics are his and he did not exaggerate; but the influence of the clock went far beyond the factory, for not only were some of the most important mechanical problems in transmitting and governing motion worked out in clockworks, but the clock, by its increasing success in achieving accuracy, crowned by the invention of the ship's chronometer in the eighteenth century, made it the model for all instruments of precision.
>
> The clock, in fact, is the paragon of automatons: almost all that we can achieve and all that we can expect in automatons was first worked out in the clock."

Marx was both mesmerised and appalled by the power of the clock. In *Capital* (Volume 1, Ch. 15) Marx describes in graphic and appalling detail (illustrated by the researches of his colleague, Engels) how the workplace became a machine regulated by time-keeping.[16]

<u>Hobson / Sombart</u>

Sombart (1902) advanced an even more ambitious thesis about the role of measurement in capitalist development. I quote here the summary provided by Hobson (1906, p. 22). Here, as elsewhere, Hobson shows that some of his best writing was devoted to a concise synthesis of others' theories:

> "'Economic Rationalism' is the suggestive name which Sombart gives to the change of spirit from the romantic adventurous money-hunting of the Middle Ages to the pursuits of modern commercialism. In this process he assigns a very significant part to the discovery and use of technical business methods in account keeping, the application of exact calculation to Industry. Two names mark the early advances towards modern book-keeping - Leonardo Pisano[17] whose *Liber Abbaci*, published in 1202, may be said to indicate the beginning of modern industry, coinciding as it did with the Venetian assault upon Constantinople; and Fra Luca, whose completed system of double entry was essential to capitalistic account-keeping. The development of book-keeping, accompanied as it was by a wide general application of rational and mathematical system throughout commerce, in the shape of exact measurement of time and place, forms of contract, land surveying, modern methods of weights and measures, city plans, public accounts, was at once an indispensable tool and an aspect of modern industry. It rationalised business, releasing it from caprice and chance, and giving it a firm objective character from the profit-making standpoint."

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[16] Two very influential economic histories of the clock are those by Cipolla (1967) and Landes (2000).
[17] He is better known to mathematicians as Fibonacci.

At the time he wrote this, Sombart was a widely respected scholar. But he became a much more controversial figure in the 1930s,[18] and in view of that some writers have denounced his theories.

Yamey (1964), by contrast, offers a balanced critique: "Sombart was right in drawing attention to accounting methods. He was mistaken in reading too much economic significance into double-entry bookkeeping." Winjum (1971) is more sympathetic to Sombart's central thesis:

> "Sombart was correct in directing attention to the relationship between accounting and the use of capitalism. The system of double-entry bookkeeping does have the capability of making a positive contribution towards economic growth. Although the ability of double entry to reveal the success or failure of a business enterprise for a specific period of time was not valued by the early English merchants, double entry's capacity to accumulate data on individual operating activities, combined with its ability to bring order to the affairs and accounts of these merchants, stimulated and rationalized the economic activities of the early English merchant. Finally, double entry permits a separation of ownership and management, thereby promoting the growth of large joint stock companies. The oldest surviving records in double entry, those of the Massari of the Genoese commune for the year 1340, reveal just such a separation. Moreover, double entry brought the concept of capital into the accounting records. This was the final step in the development of a complete accounting system. It created a structure which was capable of producing relevant accounting data reflecting the efforts, accomplishments, and status of a business enterprise. This enabled the businessman to view his activities as a coordinated whole rather than as a series of scattered operations. In this way double entry could have contributed to the gradual realization that the business itself was an entity, distinct and separate from its owners."

But perhaps the best account of Sombart is by Hobson himself.[19] As is clear in the long quotation above, Hobson stresses that the development of book-keeping was accompanied by, "a wide general application of rational and mathematical system throughout commerce, in the shape of exact measurement of time and place, forms of contract, land surveying, modern methods of weights and measures, city plans, public accounts". It was perhaps this ubiquitous use of measurement in so many areas of economic activity, rather than any element on its own, that lead to the development of modern capitalism.

Marshall

Alfred Marshall was perhaps the last economist of whom it could be said: "it's all in Marshall". This common saying usually referred to Marshall's *Principles of Economics,* but in fact his main discussion of measurement and standards was located in one of his other great works, *Industry and Trade*. Three passages from this capture his ideas on standards and measurement:

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[18] Sombart's later writings in the 1930s took an explicitly National Socialist line.
[19] See also Dohrn-van Rossum (1998, pp.8-12)

> "Exceptionally constructive are all those measures needed for explaining to people generally the claims of some new thing, which is capable of supplying a great but latent want. If the thing is in small compass, easily handled, and not costly, samples of it can be distributed in various ways. But if it is expensive, and above all if it cannot be adequately handled without considerable training, then people can be fully informed of its usefulness only by seeing it at work." (Marshall, 1920a, p.201)

> "General standardization for industrial purposes is sometimes set up at a stroke by authority of Government, or of a convention of leaders in the industries most directly concerned. Thus, for instance, the present electrical standards, Watt, Ohm, Ampère, etc. were fixed by an international convention … there is a vast advantage in the existence of definite standards, adhesion to which within less than a thousandth part may be required in certain cases." (Marshall, 1920a, p. 138)

> "A little will be said … as to the nature of the economies of manual effort which are claimed as resulting from the application of analysis, experiment and measurement to common operations." (Marshall, 1920a, p. 233)

<u>Economic History and Measurement</u>

Economic historians have given more detailed attention to measurement than modern economists. An exceptional example is Kula's (1986) massive study: *Measures and Men*. Another important collection of work is the collection of historical papers edited by Wise (1995). Porter (2001) surveys the history of measurement *within* economics, while Jeremy (1971) and Pollard (1983) provide interesting examples. As we have seen above in the references to Marx and Sombart, historical studies of measurement are able to identify some altogether grander implications than the rather more short term innovation/productivity/market-efficiency perspectives taken in the economics literature (see Part II).

As such, a survey of this historical literature would be very useful. However these implications are the cumulative effects over several centuries, and it is reasonable to assume that most readers of the present document have a shorter time-horizon in mind. For that reason, and also because it would be too ambitious an undertaking, we do not attempt such an historical survey here.

3. Some Examples: Modern and Historical

To motivate what follows, I have selected five examples to illustrate different features of the economic effects of measurement. These are not chosen because all represent the most powerful evidence of the economic returns to measurement. Nor indeed are these necessarily the most important of examples. Rather they are chosen to represent a historical and sectoral cross section and most specifically to illustrate the different ways in which measurement can generate economic benefits. One example is about the effect of measurement on productivity; two relate to measurement and innovation – though in slightly different ways; one relates to measurement and transaction costs; and one relates to measurement and health. We shall see in Section 4 that these are some of the most important generic mechanisms by which measurement contributes to wealth creation.

3.1 The Compass, Winter Sailings and the Growth of Trade

In Section 2, we noted Adam Smith's comment about the compass encouraging sailors to undertake more adventurous passages. Lane (1963) has given a detailed account of the initial effects of the compass between 1250 and 1350, when he argues that the greatest effects were felt in the Mediterranean.[20] The immediate effect was the increase in navigation during the winter months. In summer, sailors could plot their courses accurately enough using the sun by day and the stars by night, and a compass was rarely required. But in the Mediterranean winter, the skies were covered in cloud at least half the time, and navigation on a cloudy night without a compass was too risky. The seas were in effect closed for much of the winter at the beginning of the thirteenth century. But thereafter, with the availability of the compass, it would be possible to achieve a larger number of sailings in winter.[21]

The macroeconomic effect of the use of the compass can be seen in terms of increased productivity. Any ship and its crew of sailors could be used more intensively. This was obviously important in enabling the growth of trade. Of course, use of the compass went hand in hand with development of nautical charts of ever-greater accuracy, so the availability of an accurate and reliable compass should be seen as one of the factors behind the greater number of sailings and the growth of trade, but not the only factor.

From the perspective of Lane's (1963) history, it seems that Smith's remark (1776, Book 1):

> "when, from their ignorance of the compass, men were afraid to quit the view of the coast"

may not have been absolutely accurate. For as Lane says, as sailors accustomed to navigating by the sun and the stars would have been content to leave the view of the coast so long as they could see the sun during the day and the stars at night. But in the absence

[20] See also Arenson (1996), Parry (1963, 1975).

[21] Harrison's invention of an exceptionally accurate clock helped to overcome the Longitude problem and in a similar way made long distance navigation much safer, and hence increased the viability of long-distance trading routes (Sobel, 1996).

of these (in the winter) then Smith's observation was quite right and that explained why the seas were "closed" in winter.

3.2 Lift and Drag Measurement and the Wright Brothers' Flyer

In their report on the role of measurement in supporting innovation, NIST (2006) choose the example of the Wright brothers' *Flyer*, the world's first aeroplane (1903), as a very striking example of how measurement plays an essential role in invention and innovation.

In their quest to create a viable aeroplane, the Wright brothers had designed wings using data published by Lilienthal – the glider pioneer. But they were puzzled to find that these wings did not perform as well as expected. Indeed, they found that the lift generated by their wing was no more than one-third of what their calculations had suggested.

In the winter of 1901-02, they decided to carry out a series of experiments and measurements to understand better what was going wrong. They built a six foot wind tunnel from a pine box and they built some miniature wings to place in the tunnel. They then built some balances to measure lift and drag. On the face of it, these balances were crude, made from bicycle spokes, worn-out hacksaw blades and other scrap metal. But the brothers showed great ingenuity in the design of their measuring instruments, and the balances were good enough to measure aerodynamic lift of different wings of different shapes and profiles with great accuracy (Engler, n.d.).

The data obtained were an essential step in the brothers' work to design and build wings and propellers suitable for a viable aeroplane (Crouch, 2003; Jakab, 1997). But Engler (n.d.) argues that "more important than the numbers themselves are what measurements the brothers chose to make." These experiments were the first systematic attempt to measure the lift and drag produced by various wing shapes, and as Engler (n.d.) says: "if they had never done anything beyond compiling and verifying their lift and drag tables, we would still remember the Wright brothers for their substantive contribution to the development of aviation."

Crouch (2003, p.255) concludes that the tests and the balances were, "as critical to the ultimate success of the Wright brothers as were the gliders." It is no surprise then that NIST chose this case study as a most striking example of the role of measurement instruments in the development of an innovation.

While the above example is an old one, we can find similar and more modern stories in the same industry. The NMO has commissioned a series of case studies on the benefits of measurement (Sagentia, 2009), and one of these describes the role of the NMS in Rolls Royce's innovation processes. Equally, Tinseth (2009) describes how the CIPM MRA has helped to support innovation processes in Boeing.

3.3 Gas Chromatography and Essential Oils

Essential oils are used in aromatherapy to improve physical and emotional well being. Essential oils are the aromatic substances extracted from a single botanical source and have been utilised in fragrances, flavours and medicines for thousands of years. But there is general agreement amongst aromatherapists that if these essential oils are to have the desired effects, essential oils need to be of the highest quality – pure, unadulterated and natural.

Pure essential oils can be expensive to produce and sell at high prices. In view of that, and in as it is difficult for the final consumer to assess quality ex ante, it is not surprising to find that some traders try to pass off low quality oils in place of the genuine article. To protect the market for high quality oils, reputable traders need accurate and impartial measurement techniques to demonstrate to customers that their products are pure and genuine.

The method of analysis by gas chromatography emerged as a standard technique for measuring the product characteristics of essential oils in the 1970s. This technique provides a 'fingerprint' which can be used to assess the identity and purity of an oil (van den Dool, 1974). There are now a total of 33 ISO standards relating to essential oils, including ISO 7359, ISO 7609 and ISO 22972 on different methods of gas chromatography. In the UK, the Aromatherapy Trade Council (ATC) represents the vendors of high quality oils, and members of that trade body agree to: promote high quality, purity and safety; provide accurate and up-to-date information and labelling; and submit to scrutiny by their peers including a policy of random testing of the oils sold by ATC Members.

Here, then, is a good example of how accurate measurement is used to demonstrate to the customer the quality and purity of products, and hence to ensure that high quality producers can command a premium for their high quality products.

3.4 Measurement and Standards for Building Materials

Most building materials are supplied in standard forms, where the ingredients, composition and dimensions are carefully measured and standardized, so that the builder and architect can be confident of the physical properties of the materials.

For example, bricks are produced to a standard size using a standard process. While the raw material may come from a variety of locations and this gives some regional differentiation to the appearance of bricks, the composition is kept within standard limits to ensure the physical properties of the end result. BS3921 defines a performance specification in terms of size, frost resistance, salt content, compressive strength and appearance. Careful measurement of such standard bricks gives typical data on the physical properties of the brick in use, including: frost resistance, strength, water absorption, thermal movement, thermal conductivity, fire resistance, acoustic properties and so on. Similar standards and measurements are made for other building materials, including: blocks, lime, cement, concrete, timber, metals, bitumen, roofing materials, glass, ceramics, stone, plastics, glass-fibre, gypsum, plaster-board, and so on (Lyons, 2007).

In the absence of such standards and the careful measurements of the properties of materials produced to those standards, the architect and builder would face truly enormous transaction costs in procuring suitable building materials for each project. On the face of it, he would have to measure the properties of each material for himself – an unmanageable task. Indeed, it is hard to see how the architect and builder could possibly be confident of observing Building Regulations without such measurements and standards.

Here, then, is a powerful example of how the combination of standards and the measurement of materials produced to those standards, reduces transaction costs *and* makes it possible for architects and builders to meet health and safety standards. In the absence of these standards and measurements, the transaction costs would be prohibitive and either nothing would be built at all, or nothing could be built to the desired safety standards. Note, moreover, that standards on their own are not sufficient to remove the transaction costs: it requires standards *and* extensive measurement of materials produced to those standards to reduce the transaction costs.

3.5 Home-Use Blood Pressure Monitors and Treatment of Hypertension

The final example is one where the immediate benefits of measurement are felt directly by the final consumer, rather than measurement enhancing the productivity and innovation of business. It is an example where the declining costs of measurement instruments makes them affordable for home use and that may improve health diagnoses.

Self-measurement of blood pressure first started in the 1930s, but has become much more viable with the introduction of readily available and cheap electronic blood pressure monitors. McManus et al (2008) state that almost 10% of people in the UK now monitor their own blood pressure and, amongst those with hypertension, the proportion is much higher. In the United States, about two thirds of those with hypertension monitor their own blood pressure.

The traditional manual method of measuring blood pressure calls for considerable skill and experience and is therefore only viable for doctors. But now a wide variety of electronic devices are available in the UK,[22] which have been independently tested and found to meet the protocols required by the British Hypertension Society (or either (i) the protocols of the US Association for the Advancement of Medical Instrumentation, or (ii) the equivalent international protocols).

Initially, some in the medical profession were sceptical about the usefulness of 'self monitoring' but McManus et al (2008) conclude that:

- "Self monitoring of blood pressure is useful in the diagnosis and management of hypertension
- Multiple measurements of blood pressure allow a better estimation of "true" blood pressure
- Systematic reviews show that blood pressure is lower when self monitored
- Self monitored blood pressure correlates better with risk of stroke than office readings
- Patient education and clinically validated sphygmomanometers[23] are prerequisites for effective self monitoring"

[22] http://www.bhsoc.org/blood_pressure_list.stm
[23] A 'sphygmomanometer' is a blood pressure meter.

4. Adjacent Literatures within Industrial Economics

In my original report (Swann, 1999) it was useful to connect the economics of measurement to two adjacent literatures in industrial economics, because the literature on the economics of measurement, as such, was very sparse. These two adjacent literatures were: the economics of standards and the economics of research and development.

In retrospect, I think that connection was a useful one. As we see in Section 5 below, some of the pioneers of the economics of measurement (Tassey, Link and NIST) made the same connections. Tassey described measurement standards as a key part of the technology infrastructure and the role of measurement in supporting standards was indisputable.[24] Equally, many of the NIST studies drew the parallel between public expenditure on scientific metrology and public expenditure on basic research. In retrospect, however, it would be useful to draw a connection also to one further literature within economics. This concerns the treatment of measurement accuracy and measurement error in applied economics and econometrics. An essential result applies in that context: economic data can only shed light on an economic relationship of interest if the signal to noise ratio is sufficiently strong. This will be of particular use in Section 5.

In this section, we therefore give a brief summary of these three themes in the economics literature: the economics of standards; the economics of R&D; and the signal-to-noise ratio.

4.1 The Economics of Standards

The easiest way to describe the economic role of standards is to show how standards can support six key wealth-creating mechanisms.[25]

<u>Division of Labour</u>

Adam Smith (1776) noted that even in the simplest forms of manufacture, it was customary to find that the production process was divided into several distinct parts. Each labourer would work on just one of those tasks. Smith argued that this *division of labour*, as he called it, had a central role in economic development and wealth creation. For a worker specializing in one task could achieve levels of productivity far in excess of what (s)he could manage if (s)he carried out all steps in the production process.

However, the division of labour only works as a manufacturing strategy if the fruits of this divided labour can be recombined to achieve a quality finished product or service. This recombination depends on an understanding between adjacent labourers in the process. The first worker must complete his/her task in a form and to a standard expected by the second so that the second can quickly proceed with his/her own task. In short, the success of the division of labour depends on norms or standards – whether formal or informal. Smith, writing in 1776, illustrated his discussion of the division of labour with reference to the manufacture of pins but he could have chosen many other examples.

[24] Faith et al (1981) show that the issues for the USA and UK around metrication have much in common with the economic analysis of a 'standards battle'.
[25] This sub-section draws heavily on Swann (2007)

Competition in open markets

Most economists argue that competition in open markets is generally a good thing for the efficient operation of an economy. For markets to be genuinely open, a lot of conditions must be satisfied. There must be no barriers to entry which give an incumbent in the market an advantage over entrants *just because it is an incumbent*. Now, for sure, open standards cannot remove all barriers to entry. But open standards representing a balance of producer, consumer and third-party interests can help to enable open markets and hence increase competition.

Why is this? If the technological characteristics required of a product or service are not defined in a standard, then incumbents with a long history of trading have an advantage over potential entrants. The former have accumulated knowledge that enables them to produce what is required in this market. The entrant, by contrast, has to embark on reverse engineering or trial and error. By contrast, if the characteristics required of a product or service are defined in a standard, then incumbents have less of an advantage over the entrant. The open standard opens up the market to new entrants because the rules of membership are now set out on paper. Sometimes large businesses are resistant to open standards because they believe that these increase competition. They are right!

The history of the personal computer provides a powerful illustration of how the existence and use of open standards allowed many new entrants into the computer industry. The fact that IBM devised an open standard and outsourced the production of its components to many small electronics and software companies may not have helped its own long-term success in this market. But it provides a powerful example of how open standards facilitate entry, strong competition and the complete restructuring of an industry.

Cooperation to exploit network effects

In economics, a *network technology* is any technology where the value to the user depends not just on the intrinsic merits of the technology itself, but also on the size and composition of the network of other users of the same technology. *Network effects* are the additional benefits that stem from the fact that there is a large community of users. Network technologies and network effects are pervasive in the modern economy.

Economics has two ‘laws’ of network effects which describe how the value of the network increases with size. These are, to be honest, not like the laws of a precise science – such as the laws of thermodynamics – so it is better to think of them as ‘rules of thumb’. The best known is called Metcalfe’s Law. This asserts that the total value that an economy derives from a network depends on the variety of two-way communication linkages that can be built. That is roughly proportional to the square of network size. Less well known, but even more striking, is Reed’s Law. This asserts that the total value that an economy derives from a network depends on the number of groups of different sizes that can be created within the network. That depends on a higher power of network size. However, these laws only apply if there is substantial compatibility between different network members. And that, in turn, calls for ubiquitous, open standards.

Innovation

Innovation is a vital force for economic development and wealth creation: that statement seems uncontroversial. But now I assert that standardization has a central role in innovation. Some people find this assertion surprising. For example, when in 2005, the British Government's Department of Trade and Industry published a study on the economic benefits of standardization, a British newspaper reacted with the ironic headline, "Red tape can be good for business." [26]

How do standards support innovation? We can find several mechanisms at work here. First, as I said before, standards support the division of labour, and the division of labour supports certain types of innovation activity. Second, as I said before, open standards can help to open up markets and allow new entrants and as Schumpeter argued, the new entrant is a powerful force for innovation. Third, the existence of generally accepted measurement standards allows the innovative company to prove that its innovative products do indeed have superior performance. In the absence of such measurement standards, the innovator may not be able to sustain a premium for his product in the market because he cannot prove its superiority. If the innovator cannot achieve a premium for his innovations, then the economic incentive for innovation may be lost.

And fourth, once again, standards help us derive the greatest value from our networks. Open standards allow innovative entrants to take advantage of network effects, and sell add-ons which are compatible with the core technology and enhance its functionality. In the absence of open standards, such innovative entry is hard or impossible, but in the presence of open standards such entry is relatively easy and often profitable.

International Trade

The growth of international trade has been an essential driving force in economic development. Indeed, this progresses hand in hand with the division of labour and innovation, because it is the fact that different traders from different countries have specialized in different areas and have produced unique innovations that makes trade so beneficial. We know from the earliest history of trading that standards were essential for the growth of trade. We are reminded of this when we visit the great museums of the world as tourists: there we find standard weights and standard lengths in elegant forms, which date from the earliest civilizations.

Trade is a powerful force for economic efficiency. One of the main arguments for buying components from a specialist supplier rather than making them in-house is that the specialist may be able to produce the same component better or cheaper. On the other hand, one of the main arguments against buying is that dealing with an outside supplier may embroil the firm in a variety of *transaction costs* – as they are called in economics.

Transaction costs describe the costs that two parties face in doing business with each other. Transaction costs can take several forms, including the costs of ensuring that a particular supplier will produce exactly what the customer wants. Such costs can be substantial when the component is very complex and when compatibility with the customer's requirements

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[26] *The Scotsman*, 20th June (2005)

is critical. As a result of transaction costs, it may no longer seem attractive to source components from a specialist supplier, even if that supplier has potential cost advantages in production.

The use of standards can help to reduce these transaction costs. If we seek a *standard* component from an external supplier, then even if the component is a complex one, the costs of ensuring that the supplier produces exactly what we want are reduced. By reducing transaction costs, standards can make it cost-effective for companies to use the market to source specialized components. This increases the use of the market, and may indeed increase the geographical extent of the market.

Trust

The final item on our list of essential mechanisms in economic development is trust between traders. Amongst those who study corporate social responsibility there is a saying that, “ethical business is good business”. This is reassuring but perhaps surprising. For if ethical business was always the best business strategy, then there would surely be no problem of business ethics. But recent corporate scandals such as Enron demonstrate that there is such a problem The resolution to this puzzle is the assertion that even if ethical business is in the joint long-term interests of all parties to the business deal, it is not necessarily in the short-term interests of all.

In modern economics, we call this the problem of ‘information asymmetry’. If the seller knows more about the quality of the good or service being traded than does the buyer, then the seller may be in a position to exploit the ignorance of the buyer. The buyer, knowing this, is wary of buying from this supplier because he does not trust him to behave entirely honestly. In the extreme case, buyers may withdraw altogether from the market because of this lack of trust. That in turn may lead honest sellers to withdraw, if they cannot clearly distinguish themselves from the dishonest traders. The result of a lack of trust is that “bad drives out good” – an old idea, often called Gresham’s Law.

How do standards help to resolve this? Standards can help to reduce information asymmetry or reduce the problems caused by asymmetric information. If an honest trader can certify that a product conforms to a standard, then the customer can buy without facing such a risk as before. If the standards and their accreditation are open and impartial, then it is harder for one trader to exploit the ignorance of another. It is possible for customers to identify suppliers who they can trust.

Negative Effects of Standards

A summary of the economics of standards would be incomplete without a reference to the potential downside. The literature identifies four generic negative effects that may arise from standards.

The first is the possibility that *strategic idiosyncrasy* will increase barriers to entry. If a national standard is drafted with the exclusive interest of domestic producers in mind, and with no regard to the interests of domestic customers, then it can become a barrier to entry and competition (Lecraw, 1984, 1987; Mcintyre, 1997).

The second is the risk of monopolisation. There has been much discussion of how closed standards can act as a barrier to entry. Because standards-setting will often tend to generate a single monopoly standard, there is the additional risk of lock-in to an inferior standard (David, 1985).

The third is the risk that standards can raise compliance costs. This is especially relevant in the context of safety standards and environmental standards, but can apply to all types of standards. There is a risk of a particular form of regulatory capture whereby firms seek to influence standards-setters to impose a demanding standard, because although that imposes costs on the firm it will impose even greater costs on their rivals (Salop and Scheffman, 1983).

Fourth, standards can act as a constraint on product design and lead to reduced product variety. Some standards seek to define a limited variety of standard sizes in order to achieve economies of scale. The optimum product variety for the firm may be smaller than the optimum product variety for the customer (Lancaster, 1979). While this is certainly a possible problem with standards, it may not be especially important in practice.

4.2 The Economics of Research

William Thompson (Lord Kelvin) made several famous remarks on the role of measurement in science. Of these, this is perhaps the best known:

> "I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is meagre and of unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science, whatever the matter may be."

While the following is probably the most succinct:

> "To measure is to know"

Some economists on hearing this last have speculated on whether the economic role of measurement is really rather like the economic role of research: to seek knowledge. The answer to that must be "yes and no". Some measurement activities are indeed rather like research activities: so, for example, the measurements carried by the Wright brothers in their wind tunnel were very like research measurements. But some measurement activities are not at all like research activities: so, for example, the compass measurements made by a ship's captain are rarely anything like research measurements.

In view of the above, it is useful to recognise that there is a connection between measurement and research in some contexts. The economics of research has a huge literature, of course, and we cannot possibly do justice to it here. However, it is useful briefly to pick out a few themes in that literature, which will surface again later in the report.

Research is an investment, and an investment that can enjoy very high returns. But the returns are also highly variable. These rates of return are, moreover, very context specific. To quote an average is not very helpful when the variance is so very wide. For example, Griliches (1992) survey found rates of return on publicly funded agricultural research between 11 and 83 per cent.

Measurement can be seen as a form of investment, too. The firm invests in measurement to achieve a particular result, to learn some information, to establish that a product is what it purports to be, or to reduce some elements of risk. However, I am not aware of any studies that have looked at the economic returns to investments in measurement per se.

Since the returns from R&D are so unpredictable, it is seen as a relatively risky form of investment. Risk averse investors may be concerned at such risky investment, and this can lead to what is seen by some as under-investment in R&D.[27] Equally, one could expect the returns to investments in measurement to be risky. However, measurements are often made to *avoid* risk. For that reason we need to compare the total risk that obtains when there is *no* investment in measurement with the total risk when there *is* investment in measurement.

One of the most important features of research as an investment is that it is rich in spillovers. Or, to put it another way, the company paying for research can only appropriate a subset of the benefits arising from that research. The economics of R&D has discussed this both at the theoretical level and at the empirical level.

An essential theoretical foundation for the economics of R&D was provided by Arrow (1962). He explained why we may experience market failure in the allocation of resources for invention (Arrow, 1962, p. 619):

> "To sum up, we expect a free enterprise economy to under invest in invention and research (as compared with an ideal) because it is risky, because the product can be appropriated only to a limited extent, and because of increasing returns in use. This underinvestment will be greater for more basic research. Further, to the extent that a firm succeeds in engrossing the economic value of its inventive activity, there will be an underutilization of that information as compared with an ideal allocation."

Turning to empirical evidence, Griliches (1992) assessed the importance of spillovers by comparing private rates of return on R&D (to the company funding the research) to social rates of return. But it is fair to say that measuring spillovers is a difficult matter - an issue to which we return in Part 4. Jaffe (1989) and Jaffe et al (1993) found that the degree of spillovers is spatially determined. In the US context, most spillovers took place within a SMSA (standard metropolitan small area), some within a state, and few spread beyond that. Some research using bibliometrics has found similar geographical patterns.

Using a case study approach, Mansfield et al (1977) computed social returns to research by taking into account the research expenditures of related unsuccessful innovators, and the losses in rents incurred by competitors. Amongst the 17 innovations examined, the median

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[27] The "short-termism" debate stems from this observation.

social rate of return was 56 percent, at least double the median private rate of return (25 percent).

Later studies by Mansfield (1991, 1992) of the academic research results employed by 76 US firms in seven industries, calculated a rate of return in the range 22-28%. To do this, Mansfield traced innovations back to their academic source, when appropriate. He used information from the firms themselves on the importance of recent academic research for their innovations, on the time lags between the research and the first commercialisation of the relevant product, and on the total sales of each relevant product to compute a very rough estimate of the firm's returns from academic research. He found in particular that some 10 percent of new products and processes could not have been developed in the absence of recent academic research.

Another strand of the literature argues that if R&D has to be done rapidly - in response to a major competitive threat, for example - the cost of achieving the desired result will be higher than it would in calmer times.[28] Finally, some theorists have taken an *information theoretic* approach to investment in analytical measurement (e.g. Eckschlager and Stepánek, 1985). Interestingly, while information theory enjoyed some prominence in various areas of economics in the nineteen-sixties and nineteen-seventies, these have not been of lasting significance and the perspective has not found widespread use within economics.

4.3 Measurement of Economic Phenomena

While the literature on the economics of measurement is limited, we should acknowledge that the literature on *measurement of economic phenomena* is rather larger. But it is not as large as it should be.

By that, I mean the following. Morgenstern's (1963) famous book argued that economic data were not and probably could not be as accurate as econometricians seemed to assume. Nor indeed are they as accurate as they would have to be to make sense of the use to which econometric techniques are put. Morgenstern (1963, p. 116n) noted a comment made by Norbert Weiner on the first edition of his book:

> "I might add that Professor Wiener, after reading the first edition of the present book (1950), remarked that 'economics is a one or two digit science,' a comment worth pondering over, especially by those who report changes in national income, prices, etc., up to six, seven or eight "significant" digits or to hundredths of one percent."

Morgenstern said however that we should not be ashamed that our data cannot be more accurate than that. He observed that some physicists would say that a measurement accurate to 10 per cent is actually "a very good measurement" (Morgenstern, 1963, p. 97). We just need to resist using techniques which demand unattainable accuracy.

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[28] The model underlying this assertion is quite a sophisticated one, but the basic idea is this. The R&D manager in a hurry must pursue several research lines in parallel, including many that turn out to be unprofitable, whereas with less urgent work, he could pursue different research lines sequentially, leading to less wasted effort.

This is a vital message for applied economics but one that has been largely ignored.[29] Much econometrics proceeds as if measurement error is not a problem or if it is, there is nothing we can do about it, so it is best ignored. This is a bit dangerous.

The accuracy we require of our economic measurements depends on the purposes for which those measurements are used. Or, to put it another way, if we have ‘noisy’ data, let us hope that we have a very strong signal, so that the noise does not interfere much with the signal. Or, if we do not have a strong signal, then we better be sure our data contain little noise, or else we can do little with them.

This point is so important it deserves a brief mathematical exposition. Assume an underlying model relating with two normalised variables, with zero means:

$$y = bx + u$$

But in this case, *x* cannot be measured exactly, only with error:

$$\tilde{x} = x + v$$

A standard econometric result shows that the usual ordinary least squares (OLS) estimator using measured values $(\tilde{x})$ rather than true values (*x*) is inconsistent. The extent of the bias is given in the following formula:

$$\frac{b - p\lim \hat{b}}{b} = 1 - \frac{\sigma_{xx}}{\sigma_{xx} + \sigma_{vv}}$$

where σ_{xx} is the variance of the true signal and σ_{vv} is the variance of the noise (or measurement error).

If we define the signal-to-noise ratio by $SN = \sigma_{xx} / \sigma_{vv}$, then

$$\frac{b - \text{plim}\,\hat{b}}{b} = 1 - \frac{1}{1 + \frac{1}{SN}}$$

What does the formula tell us? If the signal-to-noise ratio is very large, then the second term on the right-hand side of the equation will be close to 1, and that means there is very little difference between the estimated value of *b* and the true value. In short, if the signal-to-noise ratio is very large, then any bias is very small.

But if the signal-to-noise ratio is very small, then the second term on the right-hand side of the equation will be substantially less than one, and that means that the estimated value of *b* is substantially less than the true value. In short, if the signal-to-noise ratio is small, then econometric estimation will be subject to large bias.

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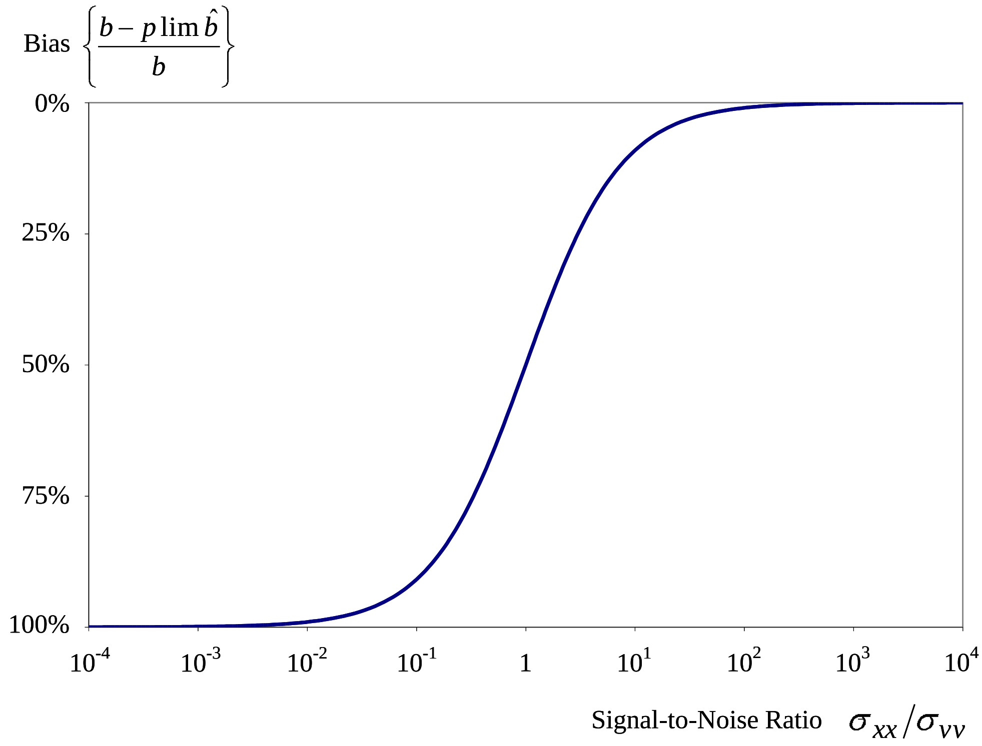
[29] See Swann (2006) for a discussion of this assertion.

For ease of interpretation, the graph below shows the nature of this relationship. The horizontal axis is on a logarithmic scale while the vertical axis is *inverted*: at the top of the scale, bias is zero, while at the bottom of the scale, bias is large.

Figure 7
Bias and the Signal to Noise Ratio in Econometric Estimation



The s-shaped relationship in this graph is an essential insight in what follows. It suggests that there are, at some stages, locally increasing returns to improved measurement accuracy (increasing the signal-to-noise ratio), while at other stages there are diminishing returns to improved measurement accuracy.

Part II: The Effects of Measurement

5. Introduction to the Modern Literature

6. Productivity

7. Innovation

8. Transaction Costs

9. Other Users of Measurement

10. Returns to Measurement Accuracy

5. Introduction to the Modern Literature

In Section 2, we discussed some of the references to the economics of measurement in the classic literature. In this section, we start our discussion of the modern literature on the economics of measurement. We start by summarising the contributions of three modern pioneers, and then summarise some of the empirical studies by NIST which, taken together, are the most influential body of applied work on the economics of measurement.

5.1 Modern Pioneers

Here I wish to highlight the work of three economists who have made pioneering modern contributions to the economics of measurement. [30]

Gregory Tassey

Tassey, Senior Economist at the US National Institute of Standards and Technology has probably contributed more than any other economist to our understanding of the economics of measurement. Two important early papers of his set the foundations for his work on measurement. Tassey (1982a) defined the idea of *infratechnologies* – these are the technologies that provide the infrastructure for further innovation and include measurement technologies. Tassey stressed three important facts about such infratechnologies: First, that they are subject to important economies of scale and scope; Second, that they are public goods; Third, that the private sector left to its own devices would tend to under-invest in infratechnologies, so that government provision and co-ordination is required. It is also natural to interpret these measurement infratechnologies as *general purpose technologies*:[31] that is, technologies which will be very widely used, and used for many different uses, and which also have much scope for improvement.

Tassey (1982b) looks at the specific instance of measurement standards as one of the infratechnologies. He argues that new measurement methods for R&D, process control, performance verification and efficiency in market transactions are all a part of the broad category of measurement standards and that they all facilitate and enable technology-based growth. Without measurements, R&D would be less credible, production processes have lower yields and higher costs, and transaction costs would be larger.

He notes that measurement technologies are more useful when adopted by all – an interesting observation which suggests that the use of measurement technologies are subject to network effects. He argues that the reasons for government involvement in the provision of measurement standards goes beyond the issue of market underinvestment noted above, and includes the arguments that economies of scope across sectors apply to measurement technology, that government-based measurement labs can maintain credibility and neutrality, and that they can take an explicitly diffusion-oriented approach.

Tassey developed and refined the arguments in subsequent work. Tassey (1991) discussed in more detail the role of government in providing a diverse technology infrastructure. Tassey (2005a) took this further and distinguished three elements to each technology: (a)

[30] An earlier study was by Poulson (1977) but I have not been able to locate a copy of that within the UK.
[31] Tassey, however, uses a different terminology – see footnote 32.

generic technologies; [32] (b) proprietary applications; and (c) infratechnologies. He stressed that it is the last of these that has the strongest infrastructure character and were therefore the most like a public good. This is why infratechnologies are the area most susceptible to under-investment (Tassey, 2005b).

Tassey (1992, 1997, 2000, 2008a, 2008b) explored in more detail the economic effects of measurement infratechnology. Three generic applications stand out: (a) test and measurement methods to describe, quantify and evaluate product attributes; (b) measurement methods as an input to research and development; and (c) measurement in manufacturing, to ensure quality and waste reduction. Tassey (1999) summarises the methodologies used in NIST impact assessment studies.

Albert Link

Link, Professor of Economics at the University of North Carolina, Greensboro, has made a very substantial contribution to the economics of innovation. His more recent work addresses entrepreneurship, government as an entrepreneur, technology transfer, university research parks and commercialization of government-sponsored research. But his earlier work included many studies relevant to the economics of measurement.

This includes his many impact assessment studies for NIST (Link 1991a, 1991b, 1991c, 1995a, 1995b, 1996a, 1997; Link and Scott, 1997) and a broader collection of work on calculating the social benefits of public R&D (Link, 1996b; Link and Scott, 2006, forthcoming), the government's role in innovation and the economic role of technology infrastructure (Leyden and Link, 1992; Link and Metcalfe, 2008; Link and Tassey, 1993). As it is not our purpose in this review to give a detailed account of impact assessment methodologies, I shall not describe these studies in detail here. But Section 5.2 summarises what we can learn from the collection of NIST impact studies (including those by Link) about the mechanisms through which measurement activity can create wealth.

John Barber [33]

Until his retirement in 2003, Barber was the Director of Technology Economics, Statistics and Evaluation at the UK Department of Trade and Industry (DTI). His paper, 'Economic Rationale for Government Funding of Work on Measurement Standards' (Barber, 1987) was a remarkable one because it anticipated so much of what later writers have said about the economics of measurement standards. Five points need special attention.

First, Barber makes a key observation about the role of measurement standards in the efficient functioning of markets. He notes that discrepancies in measurements – where, for example, there are no generally agreed standards – is damaging to the efficient functioning of markets. A lack of generally agreed measurement standards means that transaction costs

[32] Tassey (2005a) argues that: "a generic technology is not the same thing as a 'general purpose technology' (Bresnahan and Trajtenberg, 1995). The latter refers to a (homogeneous) technology with multiple market applications (i.e., economies of scope), a distinctly different concept from the generic base upon which a particular technology is developed."

[33] This section is a much abbreviated version of my paper (Swann, 2005) to a conference in honour of Barber. The full paper gives a more detailed account of how Barber anticipates the ideas of later authors.

will be high, companies decide to do things in-house rather than outsource them to more efficient specialists, and hence we lose the potential benefits from the division of labour.

Second, Barber (1987) recognised the central role of common measurement standards in the growth of international trade: "The definition of the standard needs to be universally recognised and accepted throughout the geographical area in which trade commonly takes place". This idea has entered into the *vernacular* of the measurement community. In his history of the Australian Measurement System, Todd (2004, p. 243) quotes a slogan which was adopted by measurement agencies in Australia to express its central economic role: "Tested in one place, accepted in all." Internationally comparable measurements and standards are essential to the growth of international trade.

Third, Barber is also clear about the role of measurement standards in innovation: "Without such standards it would be much more difficult for the producer of a new innovative product to indicate to potential buyers what the new product could do for them." Once again, this idea is now part of the measurement vernacular. Todd (2004, p. 243) again: "If you can't measure it, you can't improve it."

Fourth, a large part of Barber's paper is concerned with explaining when and why measurement standards are a public good. He emphasised in particular the non rivalry of benefits and that benefits are non excludable. As Barber explains, non-rivalry in consumption means that it is not desirable to charge people to use measurement standards. And in any case, non-excludability of benefits may mean that it is not possible to charge for the use of measurement standards. A large part of his paper is therefore concerned with how such open measurement standards might be funded fairly and efficiently. But Barber is careful to stress that this public good issue does not apply to all measurement activity: "Although the benefits of measurement standards as such are non—excludable the benefits of the equipment used to apply them are not."

Finally, Barber stresses that transactors must have confidence in the impartiality and integrity of measurement standards. This means that primary standards must be set in an impartial manner and that an appropriate system for calibrating and traceability must be available. The economics of measurement emphasises that trade works best when both parties to the trade have symmetric information about the items being traded. If one side has full knowledge while the other has incomplete knowledge, then these information asymmetries will generally lead to inequitable outcomes and market failure.

5.2 A Summary of NIST Studies

The influence of Tassey and Link has underpinned the many impact assessment studies of NIST which, taken together, are the most important collection of empirical studies on the economics of measurement. NIST (2003, n.d.) prepared a summary of some 29 case studies that have looked at the economic impacts of various measurement activities.[34] These are cases carried out by NIST, or by consultants on behalf of NIST. Each summary lists the most important mechanisms by which measurement is found to have economic benefits. Table 1, derived from NIST (2003), summarises their findings.

[34] The National Measurement Office also commissioned Sagentia (2009) to carry out some case studies of measurement.

Table 1
Outputs and Outcomes of NIST Laboratory Research

Industry : Project	***Year***	***Output***	***Outcomes***
Semiconductors: Resistivity	1981	Test methods	Increase productivity
Semiconductors: Thermal conductivity	1981	Materials properties Test methods	Increase R&D efficiency Lower transaction costs
Semiconductors: wire bonding	1981	Test methods	Increase productivity Increase R&D efficiency
Communications: Electromagnetic interference	1991	Test methods	Lower transaction costs
Semiconductors: Electromigration	1992	Test methods	Increase R&D efficiency Lower transaction costs
Photonics: Optical Fiber	1992	Test methods (acceptance)	Lower transaction costs
Automation: Real-time control systems	1995	Generic architecture	Increase R&D efficiency
Energy: Electric Meter calibration	1995	Test methods (calibration)	Lower transaction costs
Communications: ISDN	1995	Interoperability standards	Lower transaction costs
Computers: Software conformance	1995	Test methods (acceptance)	Lower transaction costs
Photonics: Spectral irradiance	1995	Test methods (calibration)	Increase productivity Lower transaction costs
Construction: Building codes	1996	Technical basis for standards	Energy conservation Energy cost savings
Construction: Roofing shingles	1996	Materials properties	Increase durability
Construction: Fire safety evaluation system	1996	Technical basis for standards	Lower compliance costs
Automation: Machine tool software error compensation	1996	Quality control algorithm	Increase R&D efficiency Increase productivity
Materials: Thermocouples	1997	Standard reference data (calibration)	Lower transaction costs Increase product quality
Pharmaceuticals: Radiopharmaceuticals	1997	Standard reference materials	Increase product quality
Photonics: Optical detector calibration	1997	Standard s and calibration services	Increase productivity
Chemicals: Alternative refrigerants	1998	Standard reference data	Increase R&D efficiency Increase productivity
Materials: Phase equilibria for advanced ceramics	1998	Standard reference data	Increase R&D efficiency Increase productivity
Semiconductors: Software for design automation (IGBT semiconductors)	1999	Software model	Increase R&D efficiency Increase productivity
Pharmaceuticals: Cholesterol measurement	2000	Standard reference materials	Increase productivity Lower transaction costs
Photonics: Laser and fiberoptic power and energy calibration	2000	Calibrations	Increase productivity Lower transaction costs
Chemicals: SRMs for Sulfur in fossil fuels	2000	Standard reference materials	Increase productivity Lower transaction costs
Electronics: Josephson voltage standard	2001	Standard reference materials	Increase R&D efficiency Increase productivity Enable new markets
Communications: Security (data encryption standards)	2001	Standard conformance test methods / services	Increase R&D efficiency Enable new markets
Communications: Security (role based access control)	2001	Generic technology reference models	Enable new markets Increase R&D efficiency
Chemicals: National Traceable Reference Materials Program (NTRM)	2002	Reference data Calibration services	Increase efficiency of regulatory compliance
Manufacturing: Standards for product data exchange (STEP)	2002	Standards development Conformance test methods / services	Increase quality and assimilation of standards Accelerate standards development

Source: A simplified and slightly modified version of table in NIST (2003)

The most commonly cited effects of measurement in the NIST studies are as follows:

Table 2
Most Commonly Cited Effects

Outcomes	***Number of Citations***
Increase productivity	12
Lower transaction costs	12
Increase R&D efficiency	11
Enable new markets	3
Increase product quality (or durability)	3
Cheaper / More efficient regulatory compliance	2
Energy cost savings / conservation	1

These could be further aggregated into three broad groups of effects:

- Productivity / cost reduction
- R&D, innovation, quality
- Transaction costs / new market creation

We shall use these three main headings in Sections 6 – 8 below to summarise some of the main arguments about the effects of metrology and measurement. Section 9 captures other effects omitted from Tables 1 and 2.

Looking ahead, however, it is useful to have a glimpse now of Table 3 (overleaf) which lists the 19 mechanisms identified in Swann (2003). We shall return to this in Section 12.

5.3 Surveys of the Economics of Measurement?

There are very few surveys of the economics of measurement, and most of them are not so much a literature survey so much as an overview. The closest to a full literature review is that by Birch (2003), but there are also useful reviews by Clapham (1992), Easton (2009), Poulson (1977), Semerjian and Beary (2003), Semerjian and Watters (2000), Lambert and Temple (2008).[35]

In addition, those wanting a broad review of what the economics of measurement is about will find there are some useful sources on the history of measurement, including, for example: Dilke (1987), Erwin (1960), Groom (1960), Klein (1975), Robinson (2007) and Whitelaw (2007).

[35] Seiler (1999) summarises a useful-sounding workshop on *The role of metrology in economic and social development*. The workshop proceedings are available in a PTB report (in German) but I have not had access to these in preparing this report.

Table 3
Mechanisms that Deliver Economic Returns

	Mechanism	Description
1	Better Decisions	Statistical hypothesis testing recognises Type I and Type II errors. Improved measurement can reduce the probabilities of Type I and/or Type II errors.
2	Better Standards and Use of Standards	Better measurement can help to achieve faster standards development, and better quality standards.
3	Common Pools For Product Innovation	Measurement underpins the use of novel product characteristics for competitive advantage. An open measurement system can help to create a common pool of potential product innovations.
4	Comparability Of Measurements Facilitates Trade	The growth of trade requires the reduction of transaction costs, and an essential part of that is the emergence of common standards and measurements.
5	Division Of Labour - Interchangeable Parts	Accurate and comparable measurement enables further division of labour, and greater use of interchangeable parts.
6	Dosage Issues	For a wide variety of products, precise measurements of product characteristics (or doses) are essential for efficacy and safety.
7	Easier To Demonstrate Quality And Safety	Accurate measurement of product characteristics makes it easier to demonstrate quality and safety, and hence to sustain a price premium for superior products.
8	Enabling A New Market	The creation of new forms of market is as important as other types of innovation. Measurement also plays an important role in the reduction of "market failure".
9	Enabling A New Process	Measurement is often essential to the control of complex systems that enhance productivity. Better measurement can increased process efficiency, and help to achieve energy savings.
10	Enabling A New Product	Measurability of product characteristics promotes product innovation, by making it easier to demonstrate quality, and hence sustaining a price premium for quality.
11	Improved Product Quality	Improved measurement enables quality control, allows the sorting of products by quality, enables more accurate doses, tighter tolerances and higher purity.
12	Increased Productivity / Process Efficiency	Better measurement can enable the use of new processes and/or increased process efficiency. It enables the implementation of new complex systems that enhance productivity.
13	Patent Protection	Measurement has an important role in the patenting process, which in turn enhances the profitability of the patent-owner.
14	Quality Control	Improved measurement enables quality control.
15	Reduced Costs of Meeting Regulations	Improved measurement can make it easier and cheaper to ensure regulatory compliance, and can thereby lead to a lower regulatory burden.
16	Reduced Damage from Externalities	Improved measurement can make it easier to achieve more demanding environmental regulations, and hence reduce the environmental damage from externalities.
17	Reduced Transaction Costs	The comparability and traceability of measurement reduces some of the risks in trading, and hence reduces transaction costs.
18	Shorter Times To Market	Better measurement can help companies bring products to market in a shorter time-span.
19	Testing That Equipment Is Working Properly	Measurement obviously plays a key role in testing equipment and ensuring it works properly.

6. Productivity

Some mainstream economists consider that we can represent most of the economically important effects of innovation as increases in productivity. As a general point, the present author considers that approach some way wide of the mark. However, there is no doubt that *some* of the important effects of innovations in measurement on the economy do show up as enhanced productivity.

We start this section with a case study of how measurement enhances productivity and quality and reduces waste in the context of plasterboard production. We then turn to six detailed mechanisms by which measurement can enhance productivity.

6.1 A Case Study of Plasterboard

Plasterboard is a flat sheet containing a core of gypsum hemihydrate plaster, sandwiched between two sheets of heavy paper, or ‘liner’ (Competition Commission, 1990, Ch. 3). Plasterboard originated in the United States and was introduced in the UK in 1917. Demand for plasterboard took off in earnest with the boom in house-building in the 1930s. It is now one of the essential building materials used for non-load-bearing internal walls (Lyons, 2007).

<u>The Production Process</u>[36]

The production process uses plaster, paper and energy (mainly in the form of heat). A plaster slurry is produced and then sandwiched between two sheets of paper, cut to length and dried. The plaster used is made either from natural gypsum or from gypsum produced as a by-product of some other process – most commonly, flue-gas desulphurisation gypsum (DSG), a by-product of the flue-gas cleaning process used in coal-fired power stations.

A calcination process is used to remove most of the water of crystallisation from the gypsum powder to make a suitable plaster powder. In most plants the calcination process feeds directly to the mixer at the beginning of the production line. Here the plaster powder is mixed with water and a variety of additives to produce slurry. This slurry is then fed into the paper ‘envelope’ and spread evenly across the board. The width of the board is fixed at this stage of the process and a tapered edge or square edge is formed.

The board travels down the line, during which time the plaster gradually sets. Many lines are about 400 metres long, and the speed at which the line is run depends on how long it will take for the plaster in the board to set. The setting time depends on the thickness of the board: it is around four minutes for 12.5 mm board. The thinner the board, the faster the plaster will set, and hence the faster the line may be operated.

When set (though not yet dry), the board is cut and then automatically transferred to a drying line which moves the boards through a large oven. Once dried the boards need only to be trimmed to exact length before being ready for use. Certain types of board require additional process work, but this usually takes the form of bonding some additional

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[36] This section draws on Competition Commission (1990, Ch. 3)

material to one face of the standard board. A range of boards is manufactured including boards which are resistant to fire, moisture, impact and acoustic transmission.

Measurement, Quality and Efficiency

The main costs in plasterboard production are those represented by plaster, liner paper, energy and labour. A number of technical improvements have been used over the years to increase the productivity of the process, increase the average line speed, reduce energy usage and increase the quality of the product. These improvements include: computerised process control from calcination to finished product; new cutting equipment; faster line speeds; improved drying plant; and development of chemical additives which reduce the water required to make a workable plaster slurry, thus reducing the drying time and energy required (Competition Commission, 1990, Appendix 5.4).

What is the role of measurement in these process improvements? [37] Careful monitoring and measurement of feedstock consistency, basis weight and moisture content feeds directly back to adjust the production process. Most of the quality variations in plasterboard stem from variations in the raw material, which are amplified by the use of natural materials, and it is this that creates the need for quite complex measurement. If the producer can be sure that material going in has the right characteristics then he can be confident that the material coming out will have the right characteristics. So an important aspect of measurement activity is to have a detailed profile of the material going into the process. But this is not the only measurement activity. It is also necessary to ensure the plasterboard has the right physical profile and that it is properly tapered.

In the past, taking measurements of this sort would require that a board be taken off the line towards the end of the line for testing. Now, there is automatic and nearly immediate measurement within the first 5 or 10 metres of the line, and this automatically feeds back to process control.[38]

The use of these measurements in process control ensures higher quality, less wasted product and higher productivity. Quality is higher because the automatic feedback ensures that a greater proportion of material comfortably fits the specification, and wastage is reduced because feedback is faster and automatic. This is not state of the art metrology, but integrating measurement with the process calls for intelligent customisation to the particular production line, and commissioning this process control to work properly is sometimes a challenge.

The advance in quality is essential in view of ever-tighter building regulations which define several minimum standards for board. Tests of weight, fire-resistance, impact, strength, moisture and noise attenuation for plasterboard systems depend on board manufactured within specified characteristics. As noted in Section 3.4 above, with these measurements, the architect and builder enjoys much lower transaction costs in procuring suitable building materials for each project which meets the Building Regulations, or have appropriate test certification.

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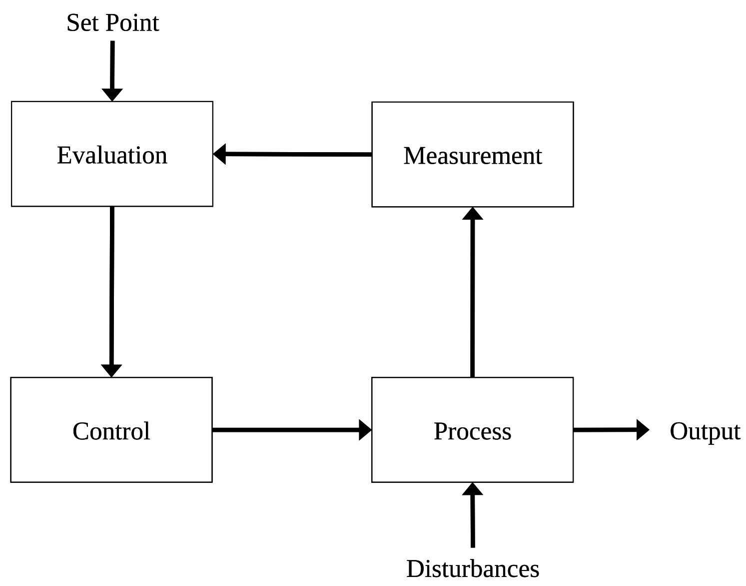
[37] The remainder of this section draws on an interview with John Colley (2009).
[38] QMT (2008) gives a more detailed account of the use of process control on a plasterboard production line.

6.2 Measurement and Process Control

In integrated process control, measurement and process controls are integrated throughout the process line, from material input to final output. Integrated process control can deliver improvements in quality and productivity some way beyond what is achieved with the ad hoc use of discrete measurement instruments. The study of measurement and its integration into real-time process control is a core part of the operations management literature, and leading texts include those by Anderson (1998), Dunn (2005), Hughes (2007), Johnson (2006), Murphy (1990), Silverman (1995), Svrcek et al (2006), Van Loon (2004) and Weiss (1987).

Measurement is one of the key components of any system for process control. Different sources use different diagrams to represent process control loops, but the following captures a synthesis of the key ideas in Hughes (2007), Johnson (2006), Svrcek et al (2006) and Murphy (1990). Many such systems can be described by the simple diagram below.

Figure 8
The Role of Measurement in Process Control



The four components are as follows:

<u>(a) Process:</u> A process is an assembly of equipment, material inputs and labour services brought together to produce an output. The process is influenced by various dynamic and environmental variables – some of which may be under the producer's control but some of which are 'disturbances'.

<u>(b) Measurement:</u> Measurement provides the information about a dynamic variable (or variables) in the process which is (are) to be controlled. The sensors or instruments used for measurement include those that measure pressure, level, temperature, flow, position, speed and other categories. The measurement is translated into an analogue or digital signal that can be used by a control system.

(c) Evaluation: In this step, the measurement is compared with a desired value (or 'set point') and a controller computes the extent and direction of any action required to correct the relevant dynamic variable, and return it to its desired value.

(d) Control: The control element in this feedback loop is the component that feeds the necessary action back into the process. In this final step, the control device (a valve, motor, pump, brake, or other device) accepts a signal from the controller and performs the necessary operation to bring the process back into balance.

Measurement has a central role as one of the four essential components of process control. Better measurement can increase process efficiency, stability and safety and can also help to economise on energy and materials. Improved measurement also enables quality control, allows the sorting of products by quality, enables more accurate doses, tighter tolerances and higher purity. In addition, measurement plays a key role in testing equipment and ensuring it works properly. This in turn may have a variety of further beneficial effects in terms of productivity, quality and safety.

Despite this, a feeling persists in some quarters that metrology is an unproductive activity and it is often an objective of production engineers to reduce metrology costs to a minimum. Kunzmann et al (2005) assess this perspective and show how, on the contrary, metrology can play a productive role in optimizing the entire manufacturing system – whether in process control, improving knowledge and know-how, performance and conformity testing, model verification, process analysis and optimization, equipment verification.[39]

A dominant paradigm in quality management today is '*Six Sigma*', which entails striving for an exceptionally low level of defects. *Six Sigma* implies no more than 3.4 defects per million opportunities, where a 'defect opportunity' is a process failure critical to the customer. *Six Sigma* was devised by Motorola Inc. in about 1985, at a time when they were facing severe competition from Japanese electronics companies and needed to make huge improvements in quality levels. According to Linderman et al (2003), *Six Sigma* makes extensive use of measurement, including 'Process Sigma measurements', critical-to-quality metrics, defect measures and other measures. Objective measurement is required at every step of the *Six Sigma* method, and measurement tools are integrated into the process at each step.

6.3 Measurement and Better Decisions

Improved measurement *can* improve decision making. I have placed the emphasis on the word '*can*' for reasons that will become clear later on. For now let us focus on the case where 'perfect' decision making simply involves applying a simple criterion to precise measurements.

Suppose that 'perfect' decision making in a particular context simply involves the following. We take a precise measurement of the variable, X, and apply the following rule:

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[39] In a similar way, Rossi et al (2002) describe the pervasive role of measurement in Total Quality Management.

If $X \leq X_c$ then *no* action is needed
If $X > X_c$ then action *is* needed

where X_c is a critical level of X. Let us suppose that this simple rule would always yield the right decision, so long as measurements are done with perfect accuracy.

In this context, measurement errors can lead to wrong decisions. We measure X with a view to applying the simple criterion described above, but the measure is imperfect. There are then four possibilities: (a) the measure indicates "no action" and that is indeed the true situation; (b) the measure indicates "no action", when the right strategy should be to "take action"; (c) the measure indicates "take action", when in truth "no action" is needed; (d) the measure indicates "take action" when that is indeed the true situation.

Figure 9 illustrates this. It shows the possible relationship between the measured value of X (horizontal axis) and the true value of X (vertical axis). For simplicity, we assume these values can lie between 0 and 1. If measurement were perfectly precise, all measurements would be arrayed along the 45° line and there would be a 1:1 mapping from measured value to true value. But suppose instead that any measured value of X is only accurate to ± r. This means, that for any measured value of X, the true value is in the range X ± r. In Figure 9 this is shown by the grey band at 45°.

Figure 9
Measurement Errors and Decision Errors

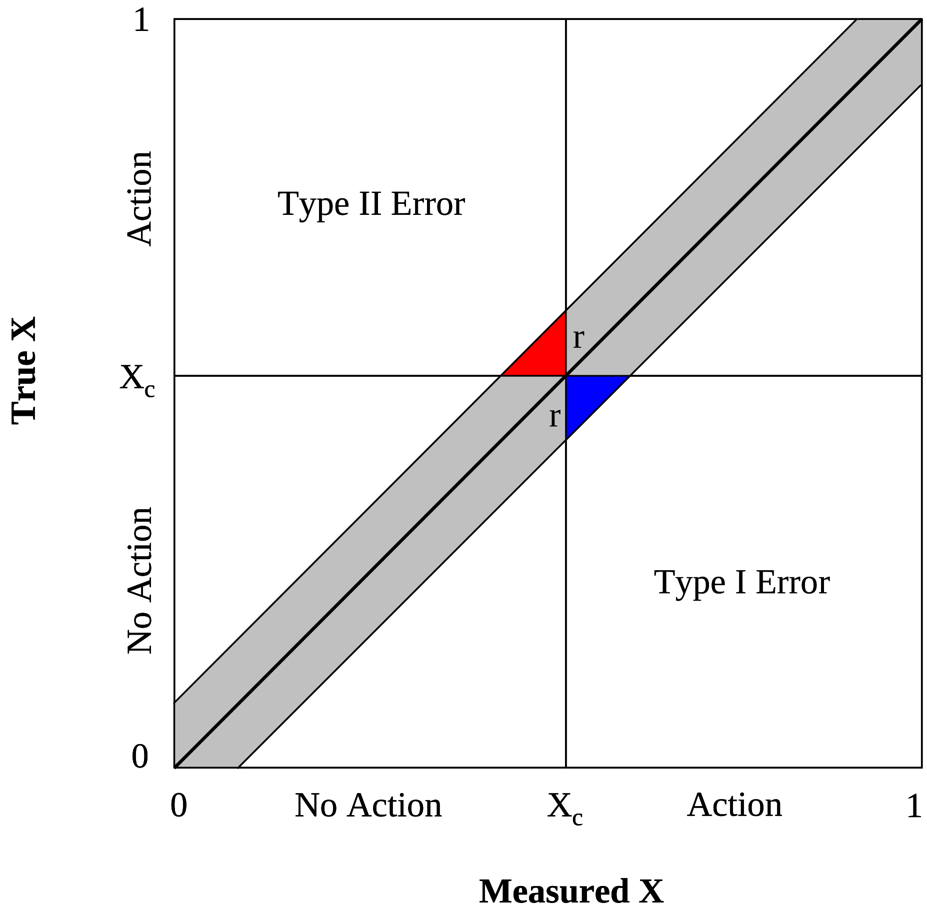

Figure 9 also marks the critical value X_c. A value of $X \leq X_c$ requires no action while a value of $X > X_c$ requires action. The figure also shows the implications of measurement error in this context. In some cases, the measured value of X is above the critical level but the true value is below the critical level. This is indicated by the blue triangle. And in some other cases, the measured value of X is below the critical level but the true value is above the critical level. This is indicated by the red triangle In these two cases, the measurement error leads to the wrong action. In the blue triangle, action is taken when it is *not* necessary. In the red triangle, no action is taken when it *is* necessary.

Statistical hypothesis testing recognises Type I and Type II errors. The first entails making a decision to reject a null hypothesis when we should not have done so; the second entails making a decision not to reject a null hypothesis when we should have done so. If we equate 'taking action' to 'rejecting a null hypothesis' and equate 'not taking action' to 'not rejecting a null hypothesis', then the blue triangle represents those cases where a Type I error is made, while the red triangle represents those cases where a Type II error is made.

In this simple model, the probabilities of Type I and Type II errors will depend on the distribution of points over the grey band. If the distribution were perfectly uniform over the whole band, then we can show that a measurement error of r = ±10% would imply a probability of making a Type II error equal to 2.6%, and the probability of making a Type I error is the same.[40] But if the distribution is more tightly clustered around the critical value X_c, then the probabilities of these errors would be larger for given r.

In this context, if measurement were perfectly precise, so r = 0, then the red and blue triangles would vanish, and there would be no errors of either type. So, in this simple model, decision errors can only arise because of measurement error in X. For that reason, improved measurement will reduce the probabilities of Type I and/or Type II errors. And perfect measurement will eliminate all Type I and Type II errors.

However, this is a rather special case. In many practical cases, mechanical application of a criterion to a small set of measures will not yield 'perfect' decision making. 'Perfect' decision making may in reality depend on perfect knowledge of a large number of factors – not just those that are measureable (X) but also some that are unmeasurable (u). In this context, some decision makers believe that paying undue attention to precise measurement of X may be counterproductive because first, it runs into diminishing returns,[41] and second it may draw attention away from understanding u, which also needs to be known. It is for this reason that we placed emphasis on the word *can* at the start of this section: improved measurement *can* improve decision making.[42]

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[40] Proof by elementary geometry. An equilateral right-angle triangle with short side 1-r will have area $(1-r)^2/2$. Hence, the area of the grey band is $1 - 2*(1-r)^2/2 = 2r-r^2$. The red and blue triangles each have area $r^2/2$. hence the ratio of the area of the red triangle to the grey band is $r^2/(2*(2r-r^2)) = r/(4-2r)$. For r = 10%, that means the probability of a Type II error (red triangle) is 2.6%. The probability of a Type I error (blue triangle) is the same.

[41] If perfect decision making requires knowledge of $X+u$, but only X can be measured, then it is easy to show that diminishing returns will set in if we concentrate only on improving the measurement of X. Let $X^*=X+\varepsilon$ (where X is the true value of X, X^* is the measured value and ε is measurement error). Then, assuming independence of u and ε, the combined uncertainty due to (i) no knowledge of u, and (ii) measurement error ε, has variance var (u) + var (ε). If we measure the returns to improved accuracy by - $d$log var(X^*+u)/$d$log var(ε), it is clear that this will show diminishing returns because var(X^*+u) is bounded below by var (u).

[42] This theme is discussed further by Redman (1999).

6.4 Interchangeable Parts

This next effect of measurement on productivity might equally be cited as an example of the effects of standards on productivity. To be precise, it is an example of how measurement and standards *combined* can enhance productivity. For these standards depend on accurate measurement: without that the standard is of little value.

We have already cited Babbage's (1835) observations on the use of measurement to enhance efficiency in production. A further step forward in efficiency and productivity was obtained when manufacturers started to use measurement standards to produce interchangeable parts. One of the first to observe this was Thomas Jefferson in 1785, after a visit to France (here quoted from Gilbert, 1958, pp. 437-438):

> "An improvement is made here in the construction of muskets, which it may be interesting to Congress to know …. It consists in the making every part of them so exactly alike, that what belongs to any one, may be used for every other musket in the magazine … I put several together myself, taking pieces at hazard as they came to hand, and they fitted in the most perfect manner. The advantage of this when arms need repair are evident. He effects it by tools of his own contrivance, which, at the same time, abridge the work, so that he thinks he shall be able to furnish the musket two livres cheaper than the common price."

The use of interchangeable manufacture in earnest started in the United States. Some authors (e.g. Gilbert, 1958, p. 438) attribute an important pioneering role to Eli Whitney's production of muskets.[43] The system was especially efficient because it facilitated the division of labour: the manufacture of the musket could be broken into many operations, each of which would be produced by a specialised workman on a specialised machine. Later writers (e.g. Woodbury, 1960; Rosenberg, 1963) have argued that the system of interchangeable parts was the joint product of efforts by Whitney, Robbins and Lawrence, Ames Manufacturing Company, Colt's armoury, and the US government armouries at Springfield and Harper's Ferry.

This method of interchangeable parts seen as an essential component of the so-called, *American System of Manufactures,* which has delivered substantial economic advantage to the USA through productivity gains (Hoke, 1986). It attracted the interest of Alfred Marshall (1920b, pp. 256-258). It was later applied to a whole range of manufactured machines: typewriters, sewing machines, bicycles, cars and so on.

The growth of this American System was a matter of concern for UK manufacturers at the time of the 1851 Great Exhibition. Landes (1999, p. 448) describes how:

> "The first hints of trouble came in American clocks and firearms, mass produced with quasi-interchangeable parts. In 1854, the British government sent a mission to the United States to look further into this 'American System'.

[43] Roe (1926) observed that: "Eli Whitney, in a letter to the War Department in 1812, stated that the British Government had on hand over 200,000 stands of muskets, partially finished or awaiting repairs. The desirability, therefore, of some system of manufacture by which all the parts could be standardized and interchangeable, was well recognized."

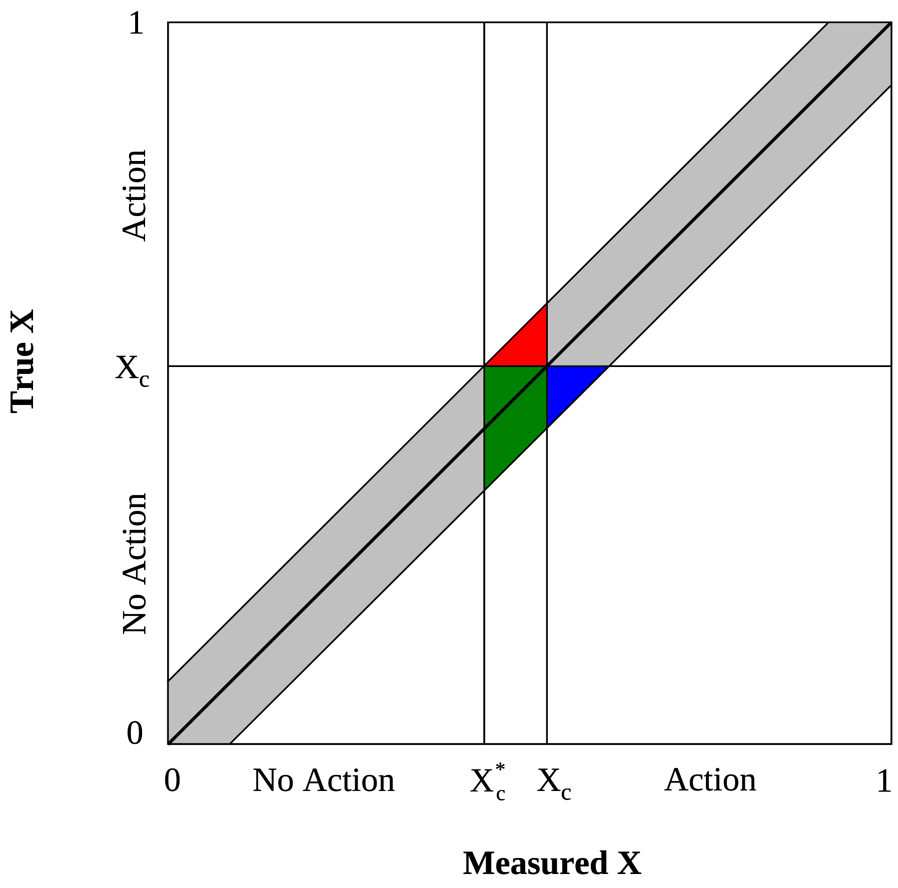
Back came the message that, yes, the British had to start learning again."

Ames and Rosenberg (1968) describe the early steps in the use of interchangeable parts in the UK. Galloway (1958, pp. 638-639) emphasises the role of Joseph Whitworth. Whitworth was a pioneer in insisting on the application of rigorous methods of measurement, and it was the application of these rigorous measurement standards that revolutionised interchangeable manufacture in the UK, and the attainable levels of productivity – especially from 1853 onwards (Galloway, 1958, pp. 638-639). The modern economics literature has given considerable attention to the benefits of interchangeable parts for productivity gains and growth (e.g. Gordon, 2004; Mokyr, 1992; Romer, 1996).

6.5 Reduced Costs of Meeting Regulations

Improved measurement can make it easier and cheaper to ensure regulatory compliance, and can thereby lead to a lower regulatory burden. And in addition, it may lead to greater compliance. The simple model of Section 6.3 can be adapted to analyse the relationship between measurement accuracy and regulatory burden. Suppose that regulations demand that a particular feature of a production process X (say a level of toxic emissions) is kept at or below a specified level X_c. So long as $X \leq X_c$ then no action is required, but if $X > X_c$ then action is required to moderate the level of X. But once again, suppose (as in Section 6.3) that the producer cannot measure X exactly, but only within a margin of error ± r.

Figure 10
Measurement and Regulatory Burden



Suppose that the producer bases his actions upon the measured value of X and uses the exact regulation (X_c) as his criterion. If the measured value of $X \leq X_c$ then he takes no action to limit emissions, but if $X > X_c$ he does take corrective action. As Figure 10 shows, in this case there is a risk that some measurements will fall below the critical level but the true value is above the critical value, and as a result the producer will not take any action and will therefore break the regulations. This is illustrated by the red triangle as shown. Equally, there is a risk that some measurements will exceed the critical level but the true value is below the critical value. In this case, the producer incurs the cost of unnecessary action.

If the regulation is 'light touch', and penalties for breach of regulations are slight, the producer may decide that the strategy described above is a satisfactory one, and (s)he expects and accepts that (s)he will make some Type I errors (blue triangle) and Type II errors (red triangle).

If, however, regulation is very strict and penalties for breach of regulations are severe, then (s)he will want to err on the side of safety. If measurement error is unavoidable, then (s)he may decide instead to use a different criterion:

If $X \leq X_c^*$ then no action

If $X > X_c^*$ then take action

where $X_c^* < X_c$. Indeed, if (s)he wishes to avoid any risk of breaking regulations and is confident that measurements are accurate within a range of ± r, then (s)he may set:

$$X_c^* = X_c - r$$

This case is shown in Figure 10. In this case, and assuming that measurements are indeed strictly accurate to ± r, there is no risk of breaching regulations. If the measured value of X is at or below this new criterion X_c^* then he can be confident that the true value of X is at or below the regulatory requirement X_c. In short, there is no risk of a very costly Type II error. But in this case, there is a much increased risk of a Type I error, and this can be costly. This is shown by the areas marked in green and blue. These represent the cases where the measured value of X indicates that the producer should take action to ensure (s)he is meeting the regulations, but the *true* value of X does in fact meet the regulations, so the action was unnecessary (and costly).

If the distribution were perfectly uniform over the whole band, then we can show that this regulation-conscious strategy will increase the probability of a Type I error (unnecessary corrective action) by a factor of four.[44] Or, if the measurement error is of the order r = ±10%, that would imply a probability of making a Type I error equal to 10.4%.

[44] As in Footnote 40, the proof uses simple geometry. Under the assumptions stated in the text, the green area is made up of three triangles the same size as the blue triangle. Hence the total area of the green and blue regions is four times that of the blue region alone.

Once again, we can use the diagram to show how improved measurement accuracy will either reduce the unnecessary regulatory burden or increase compliance (or both). As measurement accuracy improves (and r declines), then the area of the grey band declines (roughly in proportion to r) and the area of the above triangles declines (in proportion to r^2). The ratio of the red triangle area to the area of the grey band also falls. [45] And the same applies to the blue and green areas. In the limit, if r falls to zero, then there is no risk of breaching regulations and no unnecessary regulatory burden.

6.6 Two Historical Theses

The Mumford/Marx thesis (Section 2) argued that, looking over a long historical period, the synchronisation of activities (using the clock as a measurement standard) led to great advances in productivity. We cannot do justice to the thesis in this (non-historical) study, but we note some later works that have explored these issues: Blyton (1989), Cochrane (1985), Dohrn-van Rossum (1996), Hissey (1986), Marx (n.d.), Segal (2000), Strate and Lum (2000).

A more modern variant of this thesis is that careful use of measurement can support *Just in Time* (JIT) production methods, which can in principle offer substantial efficiency gains – for example by reducing stockholding costs. Sakakibara et al (1997) have explored whether companies using JIT practices perform more effectively. They found that *combination* of JIT management and infrastructure practice was related to superior manufacturing performance. They interpret their findings to imply that JIT is best seen as an overall organizational phenomenon, rather than a practice limited to the shop floor practices. An important part of the effect of JIT on manufacturing performance may come through providing improvement targets and discipline for the entire organization.[46]

The Sombart thesis (Section 2) argued that modern capitalism and modern organisational forms depend on accurate measurement – starting with accounting measurement, but extending to many other forms of measurement (including measurement of time and place, land surveying, weights and measures, city plans, and the growing application of mathematics throughout commerce.

Again, we cannot do justice to the thesis in this (non-historical) study. But there is little doubt that the advent of accounting measures and standards has reinforced the corporate division of labour between ownership and control,[47] with probable efficiency gains (but also the attendant principal-agent problems.) Pollard (1983) explores the relevance of the Sombart thesis in the context of measurement in the coal industry.

A recent study by Balconi (2002) is in a similar vein – though not cast explicitly in terms

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[45] As noted in Footnote 40, the area of the grey band is $2r-r^2$, while the red and blue triangles each have area $r^2/2$, and hence the ratio of the area of the red triangle to the grey band is r/(4-2r).

[46] Other articles on JIT and performance include Crawford and Cox (1990), Sakakibara et al (1993). In a similar fashion, Hendricks and Singhal (1997) assess whether companies using TQM achieve better performance.

[47] Meeks and Swann (2009) survey this effect and some of the other effects of accounting standards on economic performance.

of the Sombart thesis.[48] She investigated the pattern of codification of technological knowledge which occurred during the period 1980-2000, and attributes an important role to the increased availability of low cost electronic measurement instruments. She describes how this process of codification made workers' traditional tacit skills obsolete and shows that modern shop-floor operators are mainly process controllers and low-level problem solvers. But at the same time, she recognises that the acceleration of innovation has made high-level problem solvers increasingly important, so tacit knowledge remains crucial, but has become complementary to a codified knowledge base. Drawing on three detailed case studies (steel, semiconductors and mechanical industries), she illustrates the impact of codification, automation and complexity on industrial organisation. The essential character of this history is the co-evolution of technological knowledge, reduced transaction costs and the social division of labour.

6.7 Concluding Comments

The studies described in this section have been very micro-economic in character. They describe the effects and benefits of measurement at a plant or company level. In conclusion, it is worth mentioning some more macro-economic studies.

Temple and Williams (2002) [49] have used econometric analysis to provide a macro-economic assessment of the effects on metrology and measurement on GDP. Using data on R&D, patents and input–output relationships they track the nature and extent of spillover effects from measurement technology into the wider economy. Their results show that measurement R&D has a significant impact on growth, equivalent to around 2% of GDP. This benefit applies to the whole economy, but is particularly important for certain high technology and other industries. They also show that the presence of this measurement infrastructure is also important in supporting investment and export activity.

Choudhary et al (2006) develop a model of intra-industry trade in which the measurement infrastructure helps firms to differentiate their products,[50] making them more marketable, and hence promoting intra-industry trade. As an empirical test of their thesis, they consider bi-lateral intra-industry trade flows between economies in the EU.[51] They find that their measure of the cross industry importance of the measurement infrastructure (proxied by standards) and the degree of investment in the ability to measure (proxied by the use of instruments) correlate with intra-industry trade.

Ticona and Frota (2008) seek empirical evidence on whether the use of international standards and harmonized metrology procedures have an important impact on trade. For several important industrial products (including steel, bus coachwork, automotive tires and cement) they examine the relationship between product certification and the growth of production and trade. Their findings suggest that over 11% of the growth in production in these industries can be attributed to product certification.

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[48] Swetz (1987) also explores the relationship between arithmetic and capitalism though once again not cast explicitly in terms of the Sombart thesis.

[49] An earlier study by Williams was included as an appendix in PA Consulting (1999).

[50] This thesis is explored in more depth in the next section.

[51] Temple had carried out a couple of earlier studies on the role of standards in trade promotion: Temple and Urga (1997) and Swann et al (1996).

7. Innovation

The central role of measurement in innovation has been highlighted in an important recent report by NIST (2006, p. v):

> "Advanced measurement capabilities are essential to innovation in every major economic area and at every stage of the innovation process. Advanced tools and measurements are required to innovate – to design and incorporate new or better features into the kind of next-generation products and processes necessary for the United States to compete effectively and stay ahead in the global marketplace."

The sceptic might think that as an interested party, "they would say that, wouldn't they". However, there is also clear econometric evidence in support of this relationship between measurement and innovation. King et al (2006) used data on the transactions between the National Measurement System and users of measurement, and data from the Community Innovation Survey (CIS 3). They found statistically significant evidence of a positive influence of the NMS on innovation across UK industries. The impact is stronger for product innovation than process innovation, although it seems to be important for both types of innovation. They note however that the benefits also depend on the existence of a competitive and innovative testing and measurement sector, an innovative instrument sector, and a body of standards that create efficient and competitive markets for goods and services.

A later study by Temple (2008) finds: "a discernible pattern associating measurement environments with innovation outcomes, and product innovation in particular. The research indicates that measurement plays an important role in the process of creating publicly available standards, but that other channels – including the direct provision of services by the NMS – are also relevant. As important purchasers of these, technical testing and associated consultancies as well as instrument manufacturers almost certainly play a key role in transferring knowledge more widely." Temple (2008) suggests that the diffusion of metrological knowledge though the use of instruments and through instrument makers may be more important for process innovation, whereas such knowledge embodied in standards may be more important for product innovators. Furthermore, instrument makers are significant product innovators and have access to an extremely large stock of relevant standards for marketing their products.

In this section, we discuss three routes by which measurement supports and enables innovation. In the first, measurement supports the R&D and other innovative processes in the firm that lead to product innovation. In the second, measurement makes it possible for the firm to implement new production (and other) processes that are essential to the efficient production and marketing of innovative products. And in the third, measurement supports transactions between sellers of superior and innovative products and discerning customers who need to be convinced that the product is indeed superior before they will purchase. The results in King et al (2006) could be attributable to any or all of the above. We finish with a case study of Taylor Hobson, which illustrates the close inter-relationship between metrology, measurement technology and innovation.

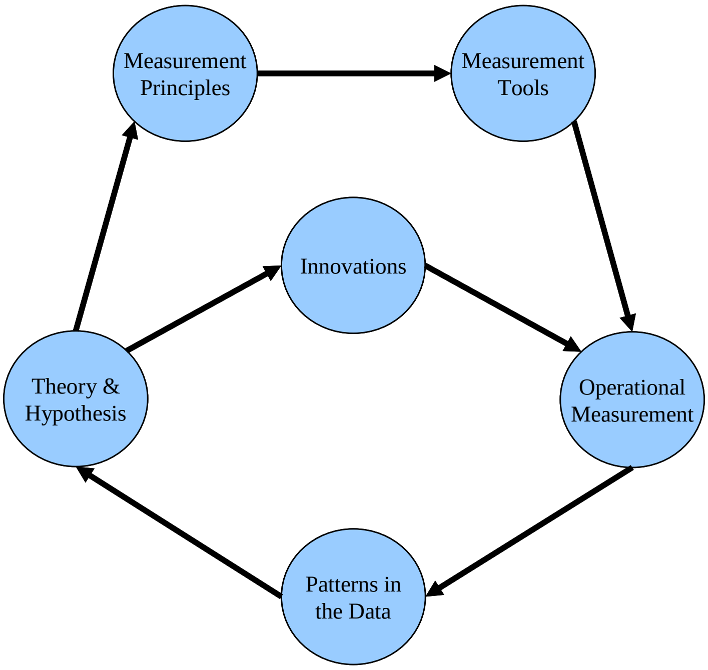
7.1 Measurement, R&D and Innovation

In this first route, measurement supports R&D and other essential inputs to innovation within companies. The basic idea is well captured by Semerjian (2006):

> "NIST innovations in measurement science and technology often become the basis for new industrial capabilities."

Indeed, this route can be described as a virtuous circle of metrology, operational measurement, R&D and innovation (see Figure 11 below). NIST's (2006) chosen example of the role of measurement in the development of the *Wright Flyer* (see Section 3.2 above) gives a very clear illustration of this virtuous circle at work.

Figure 11
A Virtuous Circle of Metrology, Measurement, R&D and Innovation



Source: Adapted from Swann (1999)

Faced with a wing that did not deliver the lift they needed, the Wright Brothers designed some crude but effective measurement tools and carried out some operational measurements in their wind-tunnel. From these measurements they were able to understand better why their original wing did not work as expected and from that could hypothesise a better design for the wing. Engler (n.d.) observes that the Wrights were the first to verify the data from their laboratory results against the performance of an aircraft in flight. So, in terms of Figure 11, they followed the loop from 'measurement tools' to 'operational measurement' to 'patterns in the data' to 'theory and hypothesis' to 'innovation' and round again with 'operational measurement'. Moreover, this use of experiment marked a change in the innovation approach of the brothers. Prior to these experiments, Engler (n.d.) argues that they were enthusiasts rather than scientists. Their success after the wind tunnel experiments came from their application of scientific method.

Equally, Tinseth (2009) gives a more modern example of how public measurement standards (the CIPM MRA) contributed to innovation within Boeing, and a similar sort of *virtuous circle*.

<u>Generic Character of Measurement</u>

NIST (2006) argues that:

> "Methods of measurement, analysis, testing, and evaluation, along with relevant standards and related databases, function as 'general-purpose technologies,' [52] valuable for their impact on the effectiveness, efficiency, and productivity of the innovation process. Like electricity and information technology, two of the most widely recognized general-purpose technologies, measurement tools have broad utility but can be leveraged in different ways."

NIST argue that new measurement methods can aid innovation in the following ways (NIST, 2006, p. 12):

- Make it easier to invent new products and processes
- Make it easier for different functions (such as research and production) to collaborate
- Enable communication across different stages of the innovation process
- Complement existing and emerging technologies

NIST observe that the value of these new measurement methods increase as they diffuse more broadly within and across business sectors. Although measurement is perhaps less 'visible' than electricity and information technology, measurement tools and methods are just as 'general purpose' NIST (2006, p. 12-13):

> "… the ability to measure accurately, reliably, and cost effectively can set the limits on what can be accomplished in the laboratory, on what can be realized on the factory floor, and on which products can be marketed at affordable prices. In short, what gets measured is often what gets done."

<u>Specific Gaps Identified by NIST</u>

The NIST (2006) survey of the measurement needs of different sectors, identifies three areas where innovation is being held back because of shortcomings in measurement:

1) Inadequate accuracy is identified as the most frequently cited measurement problem that is impeding innovation. This is the case across all sectors and technology areas, but is especially relevant in sectors with rapid technological change, such as: health care, electronics, IT, telecommunications, nanotechnology and materials. To overcome these accuracy problems, NIST considers that fundamentally innovations in measurement technologies are required.

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[52] This is a different view to that of Tassey (2005a), who emphasises that measurement is an infratechnology, and that these are different from general-purpose technologies as described by Bresnahan and Trajtenberg (1995).

2) The lack of accurate sensors is a significant barrier to process innovations involving real-time monitoring and control of manufacturing processes and environmental conditions.
3) The lack of standards, benchmarks, metrics, and protocols for assessing system-level performance of new technologies is a significant barrier to measurement and innovation in some sectors.

7.2 Measurement to Support Process Innovation

In this second route, measurement is an essential factor in the success of process innovations. As discussed in Section 6, accurate measurement is usually essential to the control of complex systems that enhance productivity. Better measurement can also enable the use of new processes and/or increased process efficiency. So, for example, in the plasterboard case study (Section 6), we saw that rapid measurement and feedback near the beginning of the production line was an essential part of a process innovation which aimed to improve product quality and reduce waste. This theme has been covered in some detail in Section 6, and at this stage we have nothing further to add here.

7.3 Measurement to Demonstrate Product Characteristics

In this third route, measurement supports transactions between sellers and customers by demonstrating to would-be buyers what are the genuine features and characteristics of the products for sole.

In Akerlof's (1970) famous paper about failure in the market for second hand cars ('lemons'), the root of the market failure is in asymmetric information. The seller knows all the good and bad characteristics of the car while the buyer cannot hope to have such detailed knowledge. Because of this asymmetric information, disreputable sellers of cars with hard-to-detect defects not only cause distress to unfortunate buyers of such cars, but they also spoil the market for reputable sellers of good quality cars. Bad drives out good.

As Barzel (1982) argues, the problem in the 'lemon' case is that measurement is really rather expensive. If it were not, then buyers could cheaply measure any of the product characteristics they want to, and they would have perfect (or perfectly adequate) knowledge about the quality of the product. It is the fact that measurement is not cheap that means the buyer bears this risk from asymmetric information. As Barzel (1982) goes on to show, in a context of costly measurement, reputable sellers use a variety of mechanisms (including warranties) to insulate buyers from the risk of buying a sub-standard product.

In a remarkable paper that anticipates von Hippel's (2005) work, Bacharach (1991) argued that product characteristics are really answers to questions about a product. But whereas much of the economics of innovation treats product characteristics as things defined by a seller, Bacharach argues that it is *not only* the seller asks (and answers) such questions. The questions may well be asked by would-be buyers, and the seller needs to answer them. This customer-centred view of the product characteristic is entirely consistent with von Hippel's (2005) view of customer-centred innovation.

This use of measurement supports the use of novel product characteristics for competitive advantage by making it easier to demonstrate quality and safety, and hence making it possible for the innovative seller to sustain a price premium for quality. Moreover, the buyer may consider that the purchase of innovative new products may embody certain risks and the buyer needs to feel a high degree trust towards the seller. Improvement in the quality and comparability of measurement helps to reduce risks and thereby to establish new innovations in the market.

Moreover, this customer-centred view makes it clear why measurement methods should be open to sellers and buyers alike. For if the discerning customer wants to ask a question about a characteristic of the product of which the seller is not especially proud, then it is essential that the customer has access to measurement methods. If these were available only to sellers and not to buyers, then such characteristics might well not be measured.

A Model of the Benefits of Measurement in Seller-Buyer Transactions

This section sets out a simple model to describe the benefits of measurement. We should stress two limitations of the model at the start. First this model only captures one aspect of what measurement does: it shows how open measurement supports transaction in innovative products by increasing the collection of product characteristics that can be measured accurately. It does not capture the mechanism described in sub-sections 7.1 and 7.2.

Second, as set out here, the model is really no more than a sketch, and some strong assumptions are made for simplicity of exposition. Nevertheless, the model is rich enough to show why the economic benefit from investment in measurement is usually a non-linear function of the size of the investment, and why it depends on the complexity of products being marketed (and hence the number of different measurement activities required).

The model is based on an economic technique called *characteristics* analysis. This starts from the unremarkable observation that different products are differentiated by the features (or characteristics) they embody. As I have argued elsewhere (Swann, 1990), we should not see product innovation as simply the improvement of particular product characteristics. As important, and often much more so, is the incorporation of *new* characteristics into products.

If each of these characteristics is treated as an axis of a multidimensional space, then it is possible to summarise the spectrum of competing products in a product *space*. The use of a space analogy turns out to be a very powerful one, because the behaviour of firms and customers in product space shows some striking similarities to their behaviour in geographical space.[53] It is found that product spaces are usually of quite a high dimension, and moreover the dimensionality often increases over time.[54]

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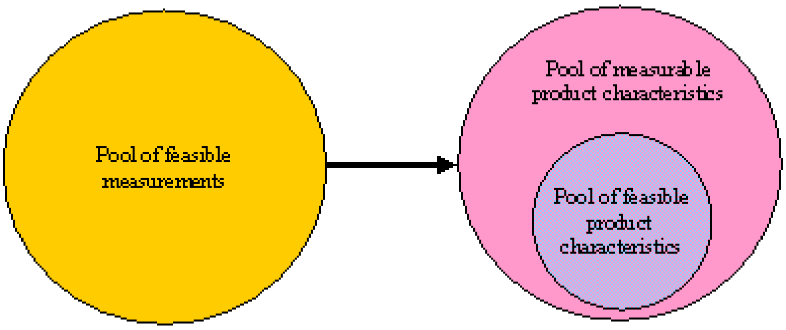
[53] For example, innovative firms often try to avoid highly congested product spaces by locating in a less congested part of the space, or more interestingly by creating a new area of the product space. There are exceptions, of course, when firms seek to cluster together - as, for example, when the network externalities from so doing are strong.

[54] The studies that have looked at this question find that 5-10 dimensions are not uncommon, and in some markets the dimensions of competition can be much higher. One study of the Japanese camera market (cited in Swann, 1990) found that an average of 3-4 new features per annum had appeared over a 20 year period - though these would not all be of equal importance.

The extent to which firms and customers can envisage and understand the space within which products are located depends on measurement. It is hard (or even impossible) to establish that one product is superior to another on some characteristic, unless that product characteristic can be measured. Accordingly, the advent of a new measurement method to measure a particular characteristic will serve to open up a new dimension of product space. When producers can demonstrate reliably that their products are indeed superior to the competition in a particular dimension, then if demand for quality is strong enough, they will be able to sustain the necessary price premium. This means that it is feasible to trade in this new part of product space, and that will be beneficial to producers and to customers who seek that sort of quality.[55]

Cumulative experience in metrology and measurement, and the work of those who develop measurement tools, defines a "common pool of feasible measurements". The more that can be measured, the more characteristics that can be measured, and hence the larger is the "pool of measurable product characteristics" – as illustrated in Figure 12.

Figure 12
Feasible Measurements and Product Characteristics



Not all measurable characteristics can necessarily be embodied in products or services, but it is reasonable to expect that as the pool of measurable characteristics increases, so also does the (smaller) pool of feasible characteristics. In short, anything that expands the pool of feasible measurements can be expected to expand the pool of feasible product characteristics.

To keep the model simple, we make the following assumptions. We take a particular market for products produced using a given technology. It is assumed that producers have available up to M product characteristics that could be used to differentiate their products. But we also assume that at most a producer will use k (< M) characteristics or features in any one product. This means that the product does not have (or achieves a score of zero) on all other features. But the choice of which characteristics are included will change as new dimensions open up. At any particular time, the number of characteristics that can be measured is taken to be m (<M) , but as the measurement programme approaches its final stages, then m approaches and finally reaches M. Until m ≥ k, the producer cannot market any products, but when m has reached this point the opportunities for competition increase.

[55] The distribution of benefit between producers and customers depends on the extent of competition.

For simplicity we assume that each characteristic is binary - either the product has that feature or it does not.

The basic idea of the "common pool" model is that the producer adds value by combining together resources from a common pool. This model stresses the *combinatorial* character of product innovation: innovators combine feasible characteristics in new ways to create new products. And the number of combinations that can be made accelerates rapidly as the size of the pool increases. Why is this? Because the number of ways of drawing k items from a population of m - when the order of sampling does not matter - is given by: [56]

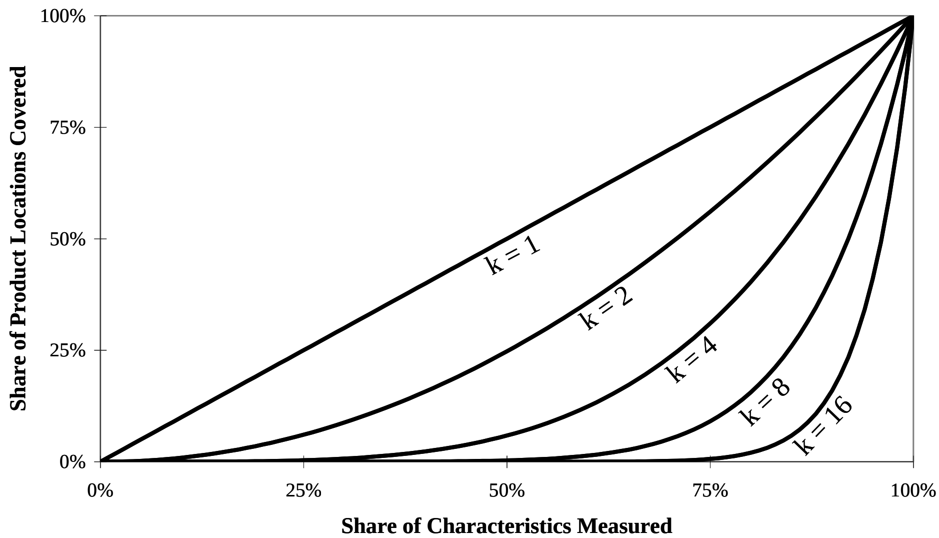
$$n \quad = \quad {}_{m}C_{k} \quad = \quad \frac{m!}{(m-k)!k!}$$

while the theoretical maximum is given by:

$$n_{\max} \quad = \quad {}_{M}C_{k} \quad = \quad \frac{M!}{(M-k)!k!}$$

which would be available when m reaches M. These equations describe the value of the common pool as the number of hypothetical products (combining k different characteristics) that can be created from the common pool (of size m). When k = 1, products just embody one characteristic each, and n = m, so that the number of marketable product locations is simply the number of characteristics that can be measured. But for k ≥ 2, n is a higher order function of m, so the number of product opportunities expands more rapidly.

Figure 13
Economic Benefits of Investment in Measurement



Source: Based on Swann (1999)

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[56] This expression is the number of combinations of k objects out of m, and m! is the factorial of m, defined by m! = 1*2*3* …. *(m-2)*(m-1)*m.

Figure 13 plots the proportion of possible product locations that are supported (n/n_{max}) by measurement as a function of the cumulative investment in measurement. The latter is measured by the proportion of all characteristics that can be measured (m/M). In Figure 13, M is set to 100, and different lines are plotted for k = 1, 2, 4, 8 and 16.

When k = 1, the relationship is linear. For larger k, the function is very skewed. With high values of k, indeed, it is only when the vast majority of characteristics can be measured that the real benefits of the measurement system are felt. Or to put it another way: if measurements are used to support complex new products with many characteristics, the real benefits from the measurement programme don't accrue until near the end.

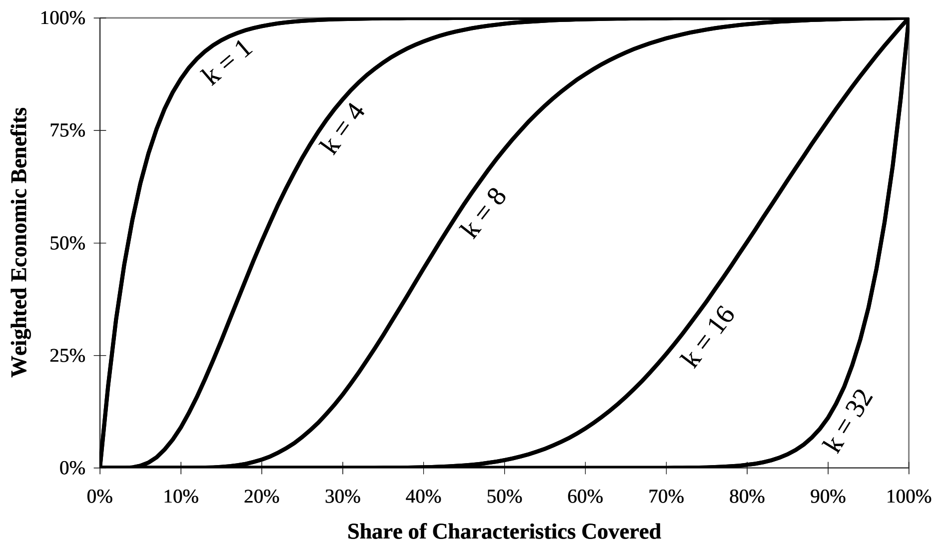
Figure 13 does, however, give an incomplete picture of the economic benefits from measurement. However the full picture is more complex. It tells us how the proportion of product locations supported increases as the measurement programme proceeds. But it doesn't necessarily follow that the economic benefits are proportional to n/n_{max} (the share of product locations that are supported). The reason is simple: it is unlikely that each measurement step is of equal significance. As the programme proceeds, it opens up new areas of product space, but these may not all be of equal value.

Suppose instead that the measurement programme is organised so that the most important measurement activities are tackled first, and the less important ones are scheduled later. For simplicity, we assume that the measurement activities are ordered neatly in declining order of importance. The economic benefit from completing activity m, and opening up that dimension of product space, is given by:

$$v(m) = e^{-am}$$

Then as the programme progresses from m-1 to m, we can weight the additional space by v(m). Figure 14 does this:

Figure 14
Weighted Economic Benefits of Investment in Measurement



Source: Based on Swann (1999)

In Figure 14, *a* has been set at 0.2, and again different lines are plotted for k = 1, 4, 8, 16 and 32. The vertical axis in this diagram shows the cumulative (weighted) economic benefits at any time divided by the final cumulative benefit at the end of the programme.

The incidence of benefits from a measurement programme over the lifetime of the programme depends critically on the value of k. For single-dimensional products, most of the benefits from the measurement programme occur at the start. As the programme matures, it may make further characteristics measurable, but this is of little commercial significance. By contrast, when products are very complex (large k) then the majority of benefits accrue at the end of the programme.[57] This is not to deny that some of the product dimensions that become available towards the end of a programme are in themselves of lesser value. But when k is large, the number of product locations becoming available grows at a prodigious rate towards the end of the programme. For intermediate values of k (k = 4 or 8 for example) we find an s-shaped curve relating economic benefits to investment.

7.4 A Case Study of Taylor Hobson[58]

Taylor Hobson of Leicester is an ultra-precision technology company specialising in surface and form metrology. The company was founded in 1886 by brothers William and Thomas Taylor, and was acquired in June 2004 by the US company AMETEK Inc.

The Taylor brothers' original business was in lens making, and during the first forty years they developed the world's highest quality cinema lenses which helped to develop the film industry in the early twentieth century. The first Cooke Lens was produced in 1893 and rapidly acquired a reputation for being the most consistent in quality worldwide. In 1932, Taylor Hobson supplied the first Cooke zoom lens for cine photography. And by 1939, Taylor Hobson were supplying over 80% of the lenses in film studios worldwide, especially in Hollywood. Taylor Hobson also produced lenses for other purposes, notably in war-time, including the *Aviar* lens for aerial photography, binoculars, and lenses for range-finders.

William Taylor had two important maxims for his business. First:

> "Never waste time in making what other people make. Devise something new that they have not thought of"

And indeed, the company had had a long tradition of what economists would call *radical* product innovation – that is products that are radically different from what has gone before. This is recognised in the economics and innovation literatures as a brave strategy, with high potential returns, but also high risks.

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[57] Paul Temple has made a very interesting conjecture that the slow rise of interchangeable manufacture (discussed in Section 6.4) may be just such an example of how the benefits from measurement may come late, requiring a sequence of product innovations in the forms of jigs and gauges, etc., as well as large homogeneous demand. Equally, he suggests that the eventual rise of mass production and Fordism was the culmination of a long sequence of measurement innovations, where once again, the main benefits come late.
[58] This case study draws heavily on information from the company website: www.taylor-hobson.com

Second, Taylor believed that it wasn't worth starting to make a product before you could measure it. Taylor examined in great detail the processes of lens making and the methods of grinding and polishing glass. Indeed, the reliability and reputation of Taylor Hobson products were achieved through rigorous quality control methods. This led to the creation of a new product group for the company - component inspection - and in due course led the company into the production and sale of metrology instruments.

In the 1930s, as Taylor Hobson began to manufacture ever more accurate lenses, they realised that they needed ever more advanced instruments to measure the perfection of each lens. But as there were no suitable instruments on the market, Taylor Hobson made their own measurement instruments. And today, indeed, it is as a supplier of ultra precision metrology instruments that the company is world renowned.

Taylor Hobson introduced the *Talysurf* 1 in 1941 - the world's first surface texture measuring instrument, which became the standard for reference and controlling surface finish. This was followed in 1949 by the *Talyrond* 1 - the world's first roundness measuring instrument. Initially, only one unit of the *Talyrond* was made and it was kept at Taylor Hobson's premises. Customers would send parts to Taylor Hobson to be measured. But as demand grew from customers, the *Talyrond* 1 went into production in 1954.

The Manufacturer (2002) notes that:

> "In the early instruments, movement of the gauge or measuring head was tied directly to the recording device; there was no storage of results or analysis beyond viewing of the graph. First solid state and then digital electronics made possible data storage, infinite analysis of results, application of advanced algorithms and viewing of results on monitors prior to printing. Manufacture of the instruments has improved to the point where accuracy in the range of nanometers is attainable and expected.

And also:

> "Originally surface and roundness instruments were built for use in gauge rooms or laboratories and were complicated to the point that only very skilled operators could use them. In the late 1960s, industry demanded simplified instruments, suitable for use by casual operators in shop floor environments. With the advent of the microchip it became possible to add more and more capability to shop floor instruments to the extent that they were sometimes as capable as laboratory versions - and nearly just as difficult to use. The current trend is towards 'simplified user interfaces' that allow operation with just a few keystrokes while all the advanced functions run in the background."

In order to stay at the front of their rapidly evolving field, the company invests heavily in R&D. At least 20% of its workforce is involved in developing and maintaining new products. They employ a research team including scientists with specialisations in physical and geometrical optics, thin films, computer-simulation, ultra-precision engineering, mechanical modelling and mathematics. Their work is leveraged by close relationships with leading academic institutions (at one University they have sponsored a chair in metrology), national measurement institutes (including the National Physical Laboratory) and industry associations (including the American Society of Precision Engineering, International Society for Optical Engineering and the European Society of Precision Engineering and Nanotechnology).

The company's history illustrates perfectly one of the key reasons why measurement equipment is so important – as discussed in Section 7.3. To support the marketing of lenses of greater and greater accuracy, it was necessary to have an instrument that would measure and demonstrate the perfection of Taylor Hobson lenses. As there was nothing available on the market, the company created its own measurement instrument. Measurement supports innovation by enabling the innovator to provide a convincing demonstration of the superiority of his devices.

8. Transaction Costs

8.1 Reduced Transaction Costs

As we saw in Section 7.3 above, in Akerlof's (1970) famous paper about failure in the market for second hand cars ('lemons'), the cause of the market failure is in asymmetric information, and as Barzel (1982) argues, the problem in the 'lemon' case is that measurement is really rather expensive. If it were not, then buyers could cheaply measure any of the product characteristics they want to, and they would have perfect (or perfectly adequate) knowledge about the quality of the product. It is the fact that measurement is not cheap that means the buyer bears this risk from asymmetric information.

The growth of trade requires the reduction of transaction costs, and an essential part of that is the emergence of common standards and measurements. The comparability and traceability of measurements reduces some of the risks in trading, reduces transaction costs and hence facilitates trade. Markets for innovative new products require a high degree of information and trust, and improvements in the quality and comparability of measurement are important for such products.

The accurate measurement of product characteristics makes it easier to demonstrate quality and safety, and hence to sustain a price premium for superior products. Because of this, measurement also plays an important role in the reduction of market failure.

Chuah and Hoffman (2004) have explored this further. They note (2004, p. 3):

> 'As transaction costs arise in the interactions between economic agents primarily as a result of information incompleteness and asymmetries between them, the major role of institutions is to, "reduce uncertainty by establishing a stable … structure to human interaction." (North, 1990, p. 6)'

And Chuah and Hoffman go on (2004, p. 3):

> 'As measurement can be readily identified as an important source of transaction cost, measurement standardization has historically been an important step in the evolution of most societies' institutions.'

Chuah and Hoffman (2004) distinguish two sorts of measurement system that arose as a result: the *evolutionary* system and the *planned* system.

Several papers by Butter and co-authors have explored the importance of trust for transaction costs (Butter, 2007; Butter *et al*, 2007; Butter and Mosch, 2003; Butter and Pattipeilohy, 2007). In those studies, Butter either measures trust directly or considers the existence of standards as a mechanism to enhance trust between buyer and seller. A measurement system of clear integrity could be expected to have a similar effect.

Butter and Mosch (2003) have studied the hypothesis that trust helps to reduce transaction costs and therefore supports trade. They estimate a gravity model of bilateral trade for 25 countries and find that different measures of trust (taken from the Eurobarometer Survey) have a positive role to play in promoting trade. They find, moreover, that the causal relationship runs primarily from trust to trade.

Butter *et al* (2007) provide an interesting example of the role of standards and measurement in reducing transaction costs relating to the standardization of container sizes, which has dramatically reduced transaction costs and the shipper's transport costs, and has radically changed the worldwide transport infrastructure. Butter (2007) shows that the fragmentation of production into ever more complex supply chains is one of the key features of globalisation, and the steady reduction of transaction costs is an important element in that. Standards and measurement play a role in reducing transaction costs and hence in this fragmentation. Moreover, this globalisation can enhance productivity. Butter and Pattipeilohy (2007) estimate a production function for the Netherlands covering the period 1972-2001, and find that off-shoring has a clearly positive effect on total factor productivity (TFP) – indeed this effect is larger than the effect of R&D on productivity.

Several of the survey/overview papers listed in Section 5.3 attribute an important role to measurement in reducing transaction costs, including especially Birch (2003), Easton (2009), Lambert and Temple (2008) and Semerjian and Watters (2000). In addition, several authors have stressed the importance of mutual recognition agreements and cooperation between different national metrology institutes to achieve the goal of reducing transaction costs (Isaev, 2007; Richter, 1999; Schwitz, 2003).

8.2 Measurement accuracy: neither overstate nor understate

There is an important lesson in Barber's (1987) paper which connects with one of the accepted principles of the theory of measurement errors. Barber argues that standards must be consistently applied so that all parties know the (same) measurement and the relevant margins of error.

As Rabinovich (1993) argues, it is generally important that those who measure do not *overstate* the accuracy of their measurements. That seems obvious enough: it does nobody any good to hide our heads in the sand and pretend our measurements are perfect. More surprising, perhaps, is Rabinovich's (1993) argument that it is also important that those who measure do not *understate* the accuracy of their measurements. Why is that?

The easiest way to see this is with a zoological example. Imagine an animal with good, but not perfect, hearing and which is constantly alert to sounds that signal danger. This animal is a bit like the statistician testing a hypothesis. There are two hypotheses: null (*no danger*) and alternative (*danger*). The animal, like the statistician, can make two mistakes. One is the type I error: to reject a true null. The other is the type II error: to fail to reject a false null. In this example it is the type II error that is critical – or perhaps I should say *fatal*. If the null hypothesis is false, but the animal fails to reject it, then the animal becomes prey to the predator. By contrast, in this case, the type I error is a more minor problem. If the null is true, but the animal rejects it, then it takes flight unnecessarily, but lives to see another day.

In this context, those who understate the accuracy of their measurements are liable to make too many type II errors. The signal may suggest danger, but this is erroneously discounted as noise because the measurement technique is considered to be too inaccurate. Consumers concerned about product safety (food safety in particular) should be careful to avoid such type II errors.

The economic importance of Rabinovich's principle will become clearer in the next section.

8.3 Some Thoughts on Asymmetric Information

Asymmetric information (between buyers and sellers) is one of three generic causes of market failure. It is unlikely that one could ever measure directly the importance of asymmetric information - for indeed, the act of measuring would to some degree correct the asymmetry. Nevertheless, it is important to understand the circumstances in which asymmetric information could arise, because these could be priority areas for public policy.

For simplicity, consider a single-characteristic product. Suppose that the measured value of the characteristic is z, where the measurement follows a normal distribution with (true) mean μ and variance σ^2. Moreover, while the producer knows the actual accuracy σ^2 of this measurement technique, the customer only has an estimate of this accuracy, s^2.

So the actual distribution of measurements is as follows:

$$z \sim N(\mu, \sigma^2)$$

but the customer thinks it is:

$$z \sim N(\mu, s^2)$$

Suppose that the customer's utility is given by:

$$U = z(1 - \phi\sigma^2)$$

But because the customer is ill-informed, he thinks the product is worth:

$$U = z(1 - \phi s^2)$$

There are three possible cases:

1. If $\sigma^2 > s^2$, then the customer is bearing undue risk, without knowing it. This could mean he ends up buying a product that he would not buy if he knew the true risk.

2. If $\sigma^2 < s^2$, then there is an Akerlof-type market failure.[59] The buyer only has a relatively inaccurate measurement apparatus at his disposal, and cannot identify good from bad.

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[59] Following the pioneering paper by Akerlof (1970). Actually, in Akerlof's analysis, $\sigma^2 = 0$ and $s^2 > 0$, so outcome 2 above is the inevitable one in his paper.

As a result, fearing that the seller will abuse his superior information, and sell him a "lemon",[60] he doesn't buy.

3. If $\sigma^2 = s^2$, then there is no asymmetric information. The seller is not in a position to exploit the customer's ignorance. If however, σ^2 is higher than it needs to be - because the latest (more accurate) measurement technologies are not being used - then the market will not be as big as it could be.

A seller of a good quality product (A) facing case 2 would have an incentive to ensure that the customer is better informed about the true quality of product A - even if the seller of a lower quality product would not. The seller of A might achieve this in a variety of ways (e.g. by obtaining independent certification that product A meets a given standard). Moreover, the seller of A would (in case 2 or 3) have a particular incentive to invest in improved measurement methods that reduce σ^2 and s^2.

On the other hand, a seller facing case 1 might not feel a strong incentive to improve the customer's information. So while it would be good for the customer to be better informed,[61] the seller would not necessarily gain from making an investment in this direction. While this argument is incomplete, and would need some further development before we can draw any firm conclusions, the example is suggestive of some circumstances in which the seller does not gain from investing to better inform the customer.

In summary, those who control particular measurement technologies will not have an incentive to create measurement technologies that demonstrate dimensions in which they are weak. This is especially relevant when the rate of addition of new characteristics is high, and hence there is a strong need for new measurement techniques to handle hitherto unmeasured characteristics.

Moreover, when we take a slightly more subtle view of what characteristics actually are, this argument can become even more important. In most of the literature on product characteristics, following Lancaster (1971), it is assumed that the characteristics themselves are defined by the producer of the product. But as discussed before, Bacharach (1991) takes a rather different approach. In his analysis, characteristics are - in effect - answers to questions about the product. These questions may indeed be highly predictable ones, posed by (and answered by) the producer. But they may also be questions posed by the consumer. In this latter case, there may well be circumstances in which it is not in the producer's interest to invest in measurement methods that improve the reliability of answers. For if the question from the consumer is one which makes the producer uncomfortable, it is probably easier for the producer if available measurement methods are none too accurate. Here is a case where the consumer needs to hear the full story, to avoid the risk of purchasing the wrong product, but it is better for the seller if that bad news cannot be articulated.[62]

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[60] American slang for a car that looks OK at auction, but breaks down as soon as you get it home.

[61] We are assuming here that the popular saying, "what you don't know can't hurt you" is false.

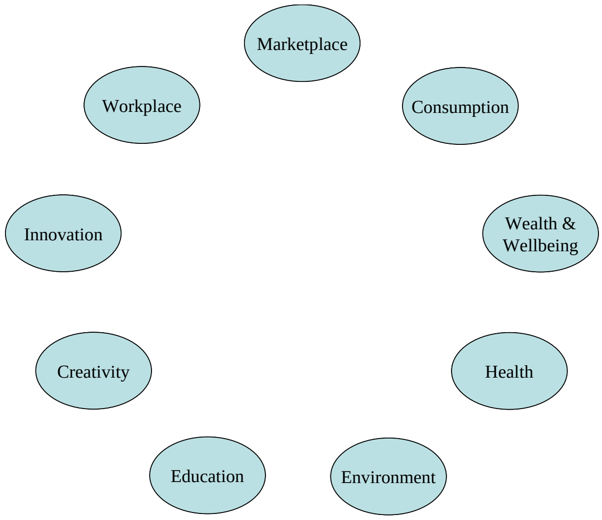
[62] A related argument is the following. It would be a good thing for the general public if a new technique for toxicity measurement were made public. However, if this new technique is created by a company that obtains strong competitive advantage from exclusive use of the technique, that company will not make it public. This competitive advantage might arise, for example, when use of the technique is necessary for regulatory approval.

In short it may well be that no producer-oriented club will have an incentive to invest in measurement methods to answer awkward questions from assertive customers. This is a priority for public policy, because with a few notable exceptions, it has generally proven very hard for consumers to achieve a "club solution" in such cases.

9. Other Users of Measurement

The discussion of measurement so far has concentrated on measurement by producers, and the use of measurement to improve the functioning of markets. These are important applications of measurement, for sure, but they are not the only applications of measurement. As we suggested in Section 1.3, we should also take a broader perspective on the role of measurement in wealth creation. This would include all the categories shown in Figure 15.

Figure 15
Beyond the 'Linear Model'



So far we have concentrated on the arc at the top left of the figure, from innovation round to the marketplace. We have discussed how measurement supports innovation, how measurement may enhance productivity in the workplace and how measurement improves the performance of the marketplace. In this section we go on beyond that to sketch *some* of the other linkages here and the role of measurement in supporting them. We start with an example of one group of measurements that are widely used by many different users for different purposes: data on food composition.

9.1 An Example of Widely-Used Measures: Food Composition Data

Measurements of the composition of different foods are needed for a wide variety of purposed by a wide variety of users. These users and uses are listed in more detail below.

In 1878, Konig of Germany published the first European food composition tables. [63] These were followed a little later by Atwater and Woods' American food composition tables in 1896. These tables incorporated over two thousand analyses of different foods, covering

[63] This brief history draws on BNF (n.d.) and EuroFIR (n.d.). A more detailed history is in Church (n.d.)

meats, cereals, fruit and vegetables, and also processed foods, such as chocolate and sausages.

After that, many other European countries followed with country-specific food composition tables. For example, the first analyses of common British foods were undertaken at the time of World War I food shortages by McCance and Widdowson. In 1949, the Food and Agriculture Organisation (FAO) published the first international set of composition tables (*Food Composition Tables for International Use*) to address concerns about world food availability. Although it is recognised that national food composition tables are more accurate, given country-to-country variations in composition, the FAO recognised that most countries simply did not have suitable tables at the time. In the 1960s and 1970s, the FAO extended these publications by producing regional food composition tables for Asia, Africa and Latin America.

Measurements of food composition are essential for a variety of purposes in many different fields of work, including assessments of nutrition, diet and health, and epidemiological research. Many uses of these measurements food composition data are generic and are used by all users, but some uses are specific to particular users.

From the information in Williamson (n.d.) and EuroFIR (n.d.), we can identify at least five main categories of user and their uses as follows, and a sixth category of 'others':

Clinical practice

Measurements of food composition are used by clinicians to analyse the diets of patients, to devise special diets for patients, and as part of their information on patients. Some medical conditions, in particular, call for specific nutritional needs and data on food composition helps clinicians to develop appropriate meal and menu plans. For example, those who have suffered severe burns need diets containing foods high in energy and proteins.

Epidemiological research

Using measurements from food composition databases, it is possible to analyse the nutrient analysis of individuals' diets and the diets of population groups. This enables researchers/ to identify patterns of nutrient intake in order to analyse possible linkages between nutrients and disease risk.

Public Health, Food Security and Education

This category covers a wide variety of uses for food composition measurement for public policy purposes, including monitoring food and nutrient availability, food security, famine relief, public health assessment, development of dietary guidelines, food regulations and food safety, consumer education, educational materials and so on.

Food Industry

The food industry needs measurement of food composition for the development of new products with particular nutritional qualities, to support food labelling and nutrient claims, and for other consumer information and marketing. These measures may also be used in conjunction with Codex Alimentarius[64] to set standards for food composition. Finally, farmers have need for food composition measures to develop appropriate diets for animals.

<u>Other</u>

Williamson (n.d.) collects several other users in this last category. Many *consumers* have an interest in food composition for a variety of reasons, including nutrition and health-related matters, and weight control. For these purposes, measures of calorie content, fat, salt, cholesterol are all important. The *food service industry* includes those catering companies providing meals for schools and other institutions, and as we learn more about the links between diet and health, consumers are becoming ever more concerned with their diet and looking for healthier options when eating out. There is therefore an increased demand on chefs and caterers to provide healthier meal options within schools, workplace cafeterias and restaurants. Related to this is the use of food composition measurements for planning 'institutional' diets (where 'institutions' include hospitals, prisons, military establishments, day-care centres and so on. Food composition measurements are also used to plan diets for athletes and sports professionals. These people, by the exceptional character of their activities, need to increase their energy and nutrient intake to meet the extra demands placed on them. Finally, food composition measurements are also used for environmental purposes – for example, in ensuring that endangered species have access to the right nutrients in their local habitat (EuroFIR, n.d.).

9.2 Measurement and the Consumer

As noted above, von Hippel (2005) writes of a 'democratic' approach to innovation where customers (whether industrial buyers or indeed final consumers) play an active part in innovation. Such customers are also likely to be active users of measurements – even if they neither own measurement instruments nor carry out the measurement activities themselves. However, as electronic measurement instruments become cheaper over time, it is likely that consumers will indeed own an increasing number of measurement instruments.[65]

Many consumers are interested in careful measurement of product characteristics to ensure quality, safety, purity, dosage and so on. The case study of Section 9.1 suggested some obvious examples in the context of food: E-numbers, calories, fat, salt, and so on. The prudent drinker will need to know about alcohol content. The prudent sunbather will want to know about sun protection factors of sun-cream or sun-block. The prudent driver will want measurement instruments that give a reliable indication of speed, petrol tank contents, coolant temperature and so on. The discerning listener will be interested in the performance characteristics of his/her hi-fi – at least up to a point. The cook will want to have reliable measures of oven temperatures and microwave power settings. And the wise householder will want reliable measuring instruments for setting central heating boiler temperature, for detecting smoke, and carbon monoxide, and so on.

[64] The Codex Alimentarius Commission was created in 1963 by FAO and WHO to develop food standards. The main purposes of this Programme are: (i) protecting health of the consumers; (ii) ensuring fair trade in food; and (iii) promoting coordination of food standards [www.codexalimentarius.net]
[65] We refer the reader back to the use of self-monitoring of blood pressure – see Section 3.5.

In short, the modern consumer depends on a wide variety of measurements for his/her own reassurance and also an increasing number of measurement instruments.[66]

9.3 Measurement and Health

The example in Section 9.1 already commented on the use of food composition measures in promoting health, through diet management and epidemiological research. But of course, the use of measurement in promoting health goes far beyond that.

Clinicians, whether in hospitals or general practice, depend on precise measurement of doses which is essential for efficacy and safety in medicines and for diagnosis of medical conditions. They also make extensive use of measurement instruments to check patient health: examples include measuring blood pressure, CT/MRI scans, blood tests, and so on. And as described in Section 3.5, some health care measurements are actually made by the patient.

Such measurements are important in managing the health care of individual patients. But they are also important in the context of epidemics. In the current *Swine Flu* epidemic, for example, accurate measurements and maps of incidence by area and age profile are critical to epidemiological forecasting and management.

This is not the place to survey all the many uses of measurements and measuring instruments in health care. But the main point to note here is that for the most part the uses of these measurements and measuring instruments are made *away* from the company or the business. The value of these measurements and instruments to society cannot adequately be measured by their contribution to business. While some health economists may crudely quantify the economic cost of illness by the loss of production, that is an inadequate measure of the overall social cost of illness. Equally, the contribution of these measurements and instruments to the wealth and well-being of society is not simply to be measured by the extra production made by people who are not ill. That is part of the benefit, but at most only a part.

9.4 Measurement and the Environment

Many measurements and measurement instruments are used by (i) those with a professional or research concern with the environment, and (ii) by companies who are bound to abide by environmental regulations in their business activities.

The objectives of these two groups – (i) and (ii) – are somewhat different. The first wishes to measure the state of the environment out of concern for it. The second have to measure what they do to the environment to ensure they are complying with regulations. For the first, the appetite for ever more accurate and wide-ranging measurements is very large and perhaps unlimited. For the second, their demand for accurate and affordable measurement is (in most cases) limited to the demands of regulation. It is clear from that that the latter are unlikely to invest as much in environmental metrology as the former. This is therefore

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[66] The useful survey by Semerjian and Watters (2000) gives many illustrations of the use of measurements to consumers (9.2), in health care (9.3) and to those who monitor the environment (9.4).

one of the more obvious cases where business left to its own devices will under-invest in metrology. We return to that issue in Part III.

The analysis of 6.5 is relevant to the case of measurements for environmental regulation. Improved measurement can make it easier and cheaper to ensure regulatory compliance with demanding environmental regulations. This can either: (a) lower the regulatory burden; (b) increase the level of compliance and hence reduce the environmental damage from externalities; or (c) both a and b.

Again this is not the place to survey the wide variety of environmental measurements used by those with concern for the environment, but it includes meteorological measurements (wind, rainfall, sunshine, temperature, etc.), pollution and emissions (including carbon dioxide emissions), geo-seismic measures, measures of the ozone layer, measures of the condition of the polar caps, and so on.

9.5 Measurement in Education and Training

The example in Section 9.1 illustrated a few of the ways in which measurement has a role in education and training. One such way was the education of ordinary consumers as to a healthy diet. Another is in the education and training of nutritionists and nutrition researchers.

Measurement has at least three roles in education and training. In the first, teaching about measurement is part of the curriculum (metrication, SI units etc.) Indeed, Faith et al (1981) argue that a lot of human capital is tied up in people's knowledge of measurement systems. Part of this is acquired in the course of work but part is acquired during education and training.

In the second role, measurement is an essential part of the research process. We recall Lord Kelvin's famous maxims about measurement from Section 4.2:

> "I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is meagre and of unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science, whatever the matter may be."

and:

> "To measure is to know"

The virtuous circle described in Section 7.1 describes the key role of measurement in research and in innovation.

And, in the third, measurement is used in education and training to assess student aptitude and performance. So, for example, there are many applications of simulators in training (e.g. for airline pilots) which measure response and performance. Measurement is often used to assess how well the athlete is responding to training. And, very generally, there is widespread use of measurement in assessing student performance on all kinds of courses – though the measurement instruments and principles used there are rather different from those used in the NMS.

A striking example of the virtuous circle of Section 7.1 above is found in one of the case studies in Swann et al (1997). It describes how a training and measurement tool was created to assess the performance of trainee surgeons at laparoscopic ('keyhole') surgery. But in addition to providing data on individual performance, one user (with responsibility for training) also found some interesting correlations in the data that could suggest a linkage between the personal and physical characteristics of the surgeon, and his or her aptitude for laparoscopic surgery. This observation completed the virtuous circle and launched another orbit, seeking new measurement principles and so on. As such, this measurement tool played a dual role: in training and in research.

9.6 Policy Implications

The main message of the above is that measurement is not only used by the producer or to make markets work better. Measurement is used more widely in many (or most) of the categories in Figure 15 that contribute to wealth creation: innovation, the workplace, the marketplace, consumption, education, environment and health.

That is an important lesson in its own right. But it also has an important policy implication. It is argued that one of the reasons why it is hard to fund metrology programmes privately, or via a club good solution, is that they are public goods. The beneficiaries from such metrology are dispersed across very many companies and industrial sectors. This makes it hard to fund the metrology by internalising externalities or by forming a club or association to fund it. But if the benefits are dispersed wider than business sectors and are felt by consumers, the education sector, the health service and environmental agencies, then that makes the public good argument even stronger.

And even if industrial associations could fund metrology themselves, it would not necessarily be the right solution to leave metrology to the private sector. For business will naturally enough focus on those areas of measurement that impact most obviously on their productivity, innovation and profitability. Areas of measurement of concern mainly to consumers, health professional, educators and environmentalists would receive less attention. This issue will be discussed again in Part III of the report.

10. Returns to Measurement Accuracy

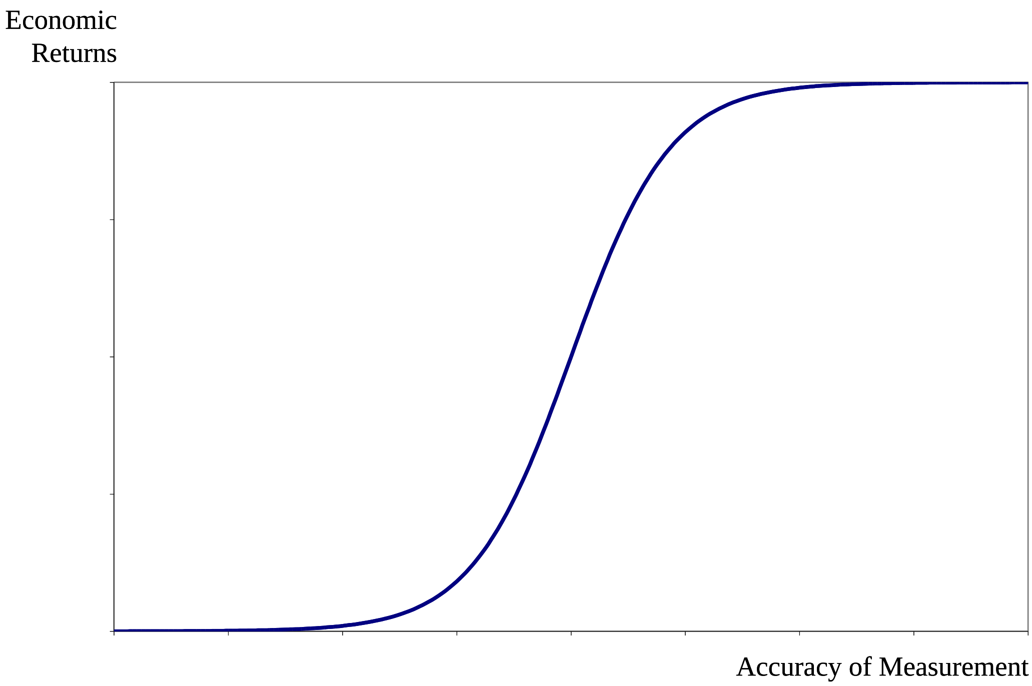
In this last section of Part II, we address the fourth of Sydenham's (2003) questions listed in the introduction: "where might it all be heading in the future?" How much more progress do we need to make in metrology and measurement now and in the future? Could there come a point when we conclude that we have most of the measurement methods we need?

Consider this example. The NMO Consultation Document says (NMO, 2009, p. 23) that current atomic clocks are accurate to one part in 10^{15} per day, but that NPL is working on clocks using optical technologies that will be accurate to better than one part in 10^{17}. A typical layman's response to this might be: "Surely one part in 10^{15} is accurate enough! Do we really need accuracy to one part in 10^{17}?" Obviously enough, there is no one answer to this: it depends on the applications we have in mind. For many applications, an accuracy of one part in 10^{15} is more than enough. For some it is just accurate enough. And for others, it is not accurate enough. NMO (2009, p. 23) indicates that this increased accuracy would enable more accurate satellite navigation systems and a new generation of high-speed computers using quantum technology.

10.1 Increasing Returns and Diminishing Returns in a Specific Application

For any one application, it would appear that a general principle applies. Initially, when the state of art in the measurement of time is not accurate enough for that application, there are increasing returns to greater measurement accuracy. Beyond a certain point, however, when attainable accuracy is good enough for that application, there are diminishing returns to greater measurement accuracy. The pattern is similar to the model of Section 4.3 above.

Figure 16
Economic Returns to Accurate Measurement for a Particular Purpose



The model used in Section 4.3 was specific to regression analysis with noisy data, but it seems likely that this generic S-shaped relationship would be relevant to many instances of this sort. The implication is that, for a particular application, it is highly probable that we encounter diminishing returns to greater accuracy beyond a certain point. The economic payoff to further accuracy typically comes from new applications that are not possible at the current state of the art.

10.2 Fractals and the Wider Economic Payoff to Accurate Measurement

To understand the wider economic benefit from improved measurement accuracy, we need a different model which is not limited to a specific application. The use of fractals would seem a natural way forward here.

Fractals

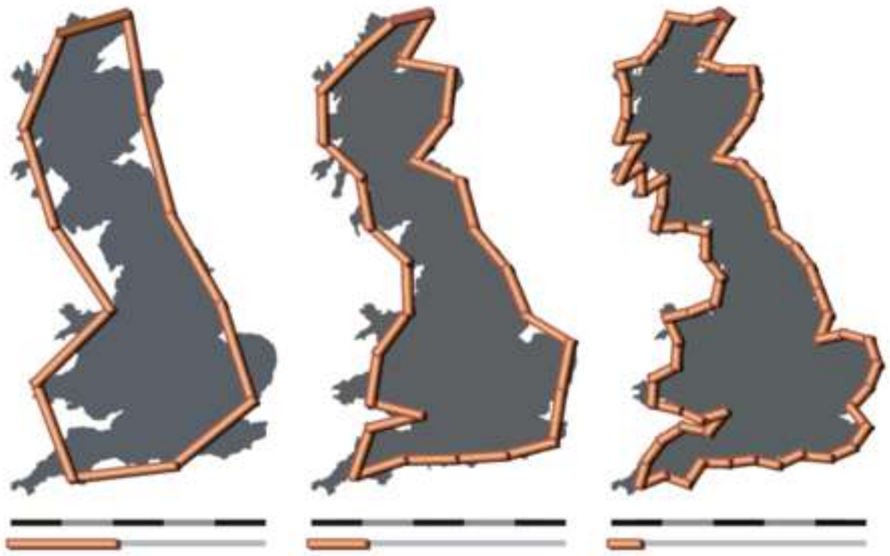
While the modern pioneer of fractals is Mandelbrot (1967, 1982) the idea goes back to earlier work by the mathematician, Lewis Fry Richardson. Richardson had a theory that the probability of countries going to war with each other was a function of the length of their common border and he sought to test this. To do so it was necessary to compile data on the length of the borders between countries, but here he was surprised to find that that there was considerable variation in the quoted lengths of international borders. For example, the border between Spain and Portugal was, at that time, variously estimated as 987 or 1214 km.

Richardson soon realised that these discrepancies stemmed from the use of different units of measurement.

It is easiest, perhaps, to explain why in the context of measuring the coastline of Britain. Suppose that a giant tried to use a ruler of 200 kilometres to measure the coast of Britain, subject to the rule that both ends of the ruler must touch the coast. Now, suppose the giant broke the ruler in half and repeated the measurement with a ruler of 100 kilometres. Then, once again, suppose the giant broke the ruler in half and repeated the measurement with a ruler of 100 kilometres. The three outcomes are as shown overleaf (Wikimedia Commons, n.d.)

It is clear that the smaller the ruler, the larger the resulting measurement of length. The reason is that when a large ruler is used, it jumps across bays, estuaries and so on, and thus approximates a complex coast-line by a straight line. (This is especially relevant to the west coast of Great Britain.) Now one might suppose that as the size of the ruler is reduced and further reduced, the computed length of the coastline would converge to a finite number, which could be called the “true” length of the coastline. But Richardson demonstrated that the measured lengths of coastlines and borders between countries appears to increase *without limit* as the unit of measurement is made smaller.

Figure 17
Measuring the Coastline of Britain with Rulers of Different Lengths



Source: Wikimedia Commons (n.d.)

Mandelbrot (1967, 1982) developed a general theory of fractals, drawing on this coastline problem. He showed that the idea applied to all kinds of space-filling curves, and that the length of such a curve could be defined (at least approximately) as follows:

$$L = k\lambda^{(1-D)}$$

Where – using the metaphor of the coastline - *L* is the length of the coastline, λ is the length of the ruler, and k and D are constants. Mandelbrot showed that D was in fact the *Hausdorff dimension* of the space-filling curve, but in this context, D is more commonly called the *fractal dimension*. From the equation above, we easily obtain:

$$\frac{\partial \ln L}{\partial \ln \lambda} = 1 - D$$

If the fractal dimension (D) is 1, then the length of the coastline is constant, regardless of λ. If the fractal dimension is greater than one, on the other hand, the measured length increases as the length of the ruler (λ) is reduced.

Wider Economic Payoff to Accurate Measurement

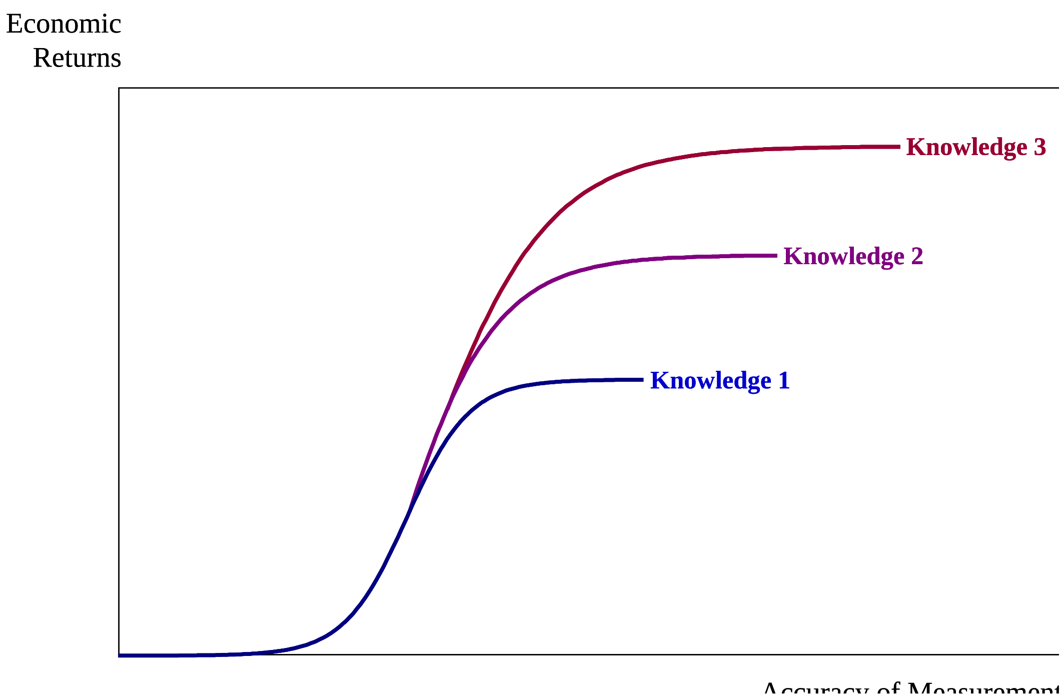
As the fractal dimension describes the effects of more detailed measurement, it seems natural to use the concept to describe the economic returns to greater measurement accuracy. If we replace length (L) by wealth (W) we have:

$$\frac{\partial \ln W}{\partial \ln \lambda} = 1 - D$$

The overall economic effects of measurement accuracy depend on the fractal dimension. Suppose $D \approx 1$: then there is *little* economic benefit from more accurate measurement. By contrast, suppose $D >> 1$: then there is *substantial* economic benefit from more accurate measurement. Indeed, the elasticity of wealth creation with respect to advance in measurement is simply given by $1\text{-}D$.

In this context, however, it is unlikely that D would be constant over the full range of λ. It is more likely that D would be constant up to a certain level of measurement accuracy but would tail off above that. This would mean that the overall economic returns to advanced measurement will start to show diminishing returns as shown.

Figure 18
Overall Economic Returns to Accurate Measurement



The curves here show (on a log scale) the relationship between overall economic returns and measurement accuracy at different times – with different levels of knowledge (1, 2 and 3). In all cases, there are diminishing returns to further advances in measurement accuracy. But with greater knowledge (the increase from knowledge 1 to 3), people know more about how to use increased measurement accuracy to create wealth.

A good example with which to illustrate the economic returns to ever finer measurement accuracy is Moore's Law in the semiconductor industry. Moore's Law states that the number of active components per semiconductor chip will double every two years. This happens because advances in measurement, technology and fabrication equipment make it possible to produce ever more miniature components. The returns to measurement accuracy are as shown in Figure 18 above. For a given stage of Moore's Law, there are substantial benefits from increased measurement accuracy up to the 'state of the art' in chip design, but beyond that, we see rapidly diminishing returns to further increases in measurement accuracy. (This would be the curve marked 'knowledge 1'.) But later on, when Moore's Law has progressed further, the benefits continue to accrue to a higher standard of measurement accuracy, though once again, there are rapidly diminishing returns to further increases in measurement accuracy beyond that.

If Moore's Law were to continue forever, then we could imagine that the *envelope* of all the curves for different levels of knowledge would be an upward-sloping straight line from the bottom left of Figure 18. However, it is generally agreed that Moore's Law cannot continue indefinitely – for a combination of reasons (fundamental physical limits, economic factors and environmental factors).

So does this suggest that in the context of Moore's Law, ever greater measurement accuracy will over time continue to create wealth? At first sight, the answer might appear to be "yes", but it is actually more complex, for two reasons.

First, in addition to Moore's Law, we also have to bear in mind Wirth's Law, which asserts that software gets slower as rapidly as hardware becomes faster. Why is that? It is often put down to what is called 'software bloat'. Wirth (1995) argues that software bloat means that the size of software surpasses its functionality, partly because designers get lazy, partly because of a version of Parkinson's Law ("Software expands to fill the available memory"), and partly because software designers include all kinds of potentially useful functions which are in fact only used by a small minority.

If Wirth's Law is right, then the net effect of Moore's Law for the user of packaged software is (to a first approximation) to stand still. In that case, the greater hardware functionality and speed is squandered by slower and more wasteful software. However, Wirth's Law is perhaps a bit of an exaggeration. Moreover, for the user of custom designed software, software bloat may be less of an issue and therefore Moore's Law does continue to create wealth for users.

Second, we need to ask for whom Moore's Law creates wealth? The returns to chip manufacturers (such as Intel and AMD) are huge and so also are the returns to leading software producers who use the technological opportunity offered by Moore's Law to market ever more complex (and memory hungry) versions of their software. But is the effect for the user so strong? Some would argue that it is not – for the reasons described before. The user of packaged software may find that the benefits of Moore's Law are offset by the problem of software bloat.

Part III: Public Policy

11. Rationale for Public Funding

This part of the report looks at the rationale for public funding of (some) measurement activities. The analysis that follows examines *why* there is a case for public funding while Section 12 tries to describe *what should be prioritised*?

11.1 Generic Rationale

The economic justification for industry policy tends to be one of three sorts. First, that policy is required because there is *market failure* requiring some sort of correction, or at least compensating activity. Second, policy is needed to *regulate* private monopolies (though this could be seen as a special case of the first). Third, a "strategic" rationale - for example, those programmes designed to give a new industry a boost (or "kick-start") so that it moves onto a faster growth curve.

In the case of NMS, the main rationale for public policy is the first sort – "market failure". Left to its own devices, the market would not necessarily generate the right portfolio of measurement activities.

Economists tend to identify three generic causes for market failure. The first is that *externalities* (whether positive or negative) drive a wedge between private and social returns from a particular private investment. If externalities are positive, some socially desirable investments will not appear privately profitable, so the market does not support enough activity. If externalities are negative, some socially undesirable investments nevertheless appear privately profitable, so the market supports too much activity.

The second is where economic activities are subject to *increasing returns*. In that case there is no unregulated market outcome that is also economically efficient. If perfect competition is sustained, then production does not exploit the increasing returns, so costs are not minimised. If monopoly is allowed to emerge, the monopolist may be able to exploit the increasing returns, but is liable to restrict output to keep up prices.

The third is that *asymmetric information* between buyers and sellers can make it impossible to find a price at which to trade that is acceptable both to buyers and to sellers. One example of this is Gresham's law which asserts that "bad drives out good". The presence of "bad" products in a market, and the inability of the buyer to distinguish bad from good *ex ante*, means that the supplier of good withdraws his produce from the market as he cannot raise a satisfactory price (Akerlof, 1970).

Which of these are relevant in the case of metrology and measurement? It is arguable that all three are relevant in this context, but probably the first two are the most important in providing a case for public policy towards metrology. This reflects the public good character of metrology. It is certainly the case that metrology funded by one agency can generate positive externalities for others. In that case, there is a tendency towards under-provision of privately funded metrology. Barber (1987) and Tassey (2005b) lay great emphasis on this tendency towards under-provision.

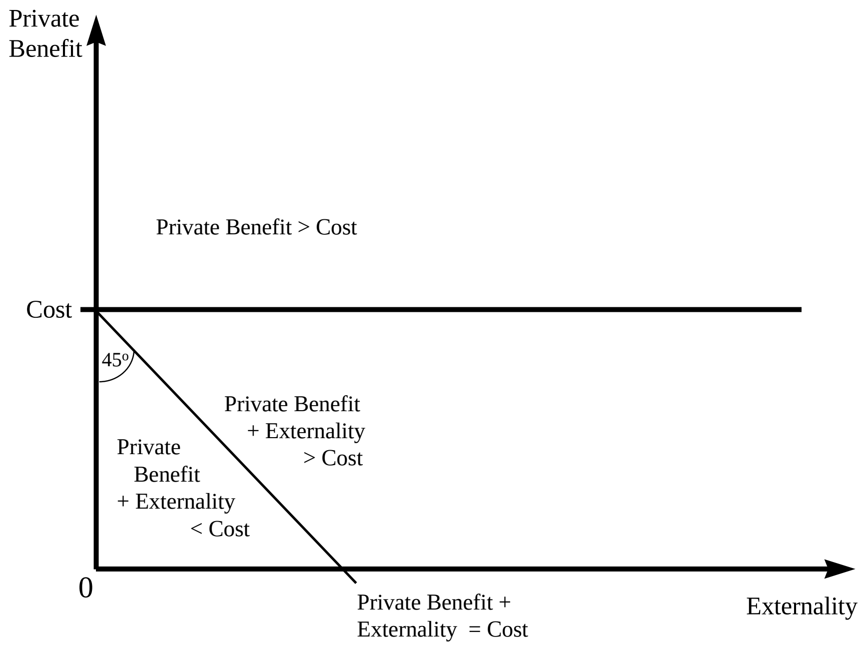
It is also the case that metrology involves substantial fixed costs and relatively small marginal costs (as described in Section 1) and therefore there are increasing returns in supplying metrology to an increasing number of users. This also brings out the public good character of metrology: it is far more efficient to coordinate production of metrology in one place and supply the outputs to all.

One important economic function of the NMS is of course to correct the information asymmetries described in earlier sections. However, this does not necessarily imply that there is information asymmetry between the producers and users of metrology. Metrology acts to reduce information asymmetries elsewhere in the economy, but the market for metrology is not necessarily afflicted by asymmetric information between sellers and buyers.

11.2 Why do externalities matter in assessing NMS priorities?

Figure 19 can be used as a map of the private benefits, costs and externalities from particular NMS projects.

Figure 19
Private Benefits and Externalities



Source: Swann (1999)

Any particular project can be located as a point in this map. Projects located above the horizontal line labelled "cost" are privately profitable, while those below the line are not privately profitable. But that is not the end of the matter. The diagonal line, at 45° to the vertical axis, shows all the projects for which the total social benefit - i.e. private benefit plus externality - is equal to cost. Projects above and to the right of this line are socially worthwhile, while those below and to the left are not.

Accordingly, Figure 19 is divided into three regions. Above the horizontal line are projects that are both privately and socially profitable. These should happen anyway, without any additional activity on the part of NMS. Indeed, there is no point in the NMS funding such activities as there will be no additionality. Below and to the left of the diagonal line are projects that are neither privately nor socially profitable. These should not take place. But in the third region - above and to the right of the diagonal line but below the horizontal - are those projects that are socially worthwhile but not privately profitable. These are the projects on which NMS activity should, arguably, be focused. These are the projects which, if publicly funded, will bring additionality. Without public funding, they will not happen; with public funding, they will.

At the risk of labouring the point, it is worth stressing that the above observations have an important implication for the choice of an empirical methodology to value measurement activities. Any technique that focuses on the "bottom line" value of a project to the proximate users will find it harder to assess any spillover benefits. As such it can only generate an *incomplete* measure of the economic benefits from measurement.

Moreover, it is worth drawing out one further implication of the above. Suppose that measurement activities are allocated between private and public sector as follows. Those where the private return is in excess of the cost are purely privately financed, while those where the full social return exceeds the cost but the return to proximate users does not will be funded by the public sector. If an *incomplete* methodology is used, then two results will follow:

- private sector projects will be measured to have a higher benefit to cost ratio than public sector projects

- public sector projects will not appear to be worthwhile

These "findings" will resonate with some political perspectives, perhaps. But the "findings" have nothing to do with the true social merit of the different projects. They simply follow from the unavoidable measurement error inherent in using an incomplete empirical methodology, and from the fact that privately funded projects are privately profitable while publicly funded projects (by definition) are not.

11.3 Internal or External?

Section 11.2 showed why externalities are important in assessing priorities within NMS. But why do they arise at all?

The basic point is if a single company or group of companies invest to create a new or better method of measuring a product characteristic that will yield financial benefits to them, but will also benefit some other companies who are not party to the project. To the extent that these spillover benefits accrue to companies who are external to the project, and are not charged for these benefits, then the spillovers can be called externalities.

A typically "Coaseian" [67] response to this observation would be: why do the project

[67] So called after followers of economist, R. Coase (1960, 1974), another winner of the Sveriges Rijksbank Prize in Economic Sciences in Memory of Alfred Nobel.

managers not require those third parties that enjoy the spillovers to join the group paying for the project, and hence *internalise* these spillovers? Indeed, economists in this tradition argue that there are fewer pure public goods than is commonly supposed. Even the lighthouse - often cited as the purest form of a public good - is no such thing, they assert. They point out that when lighthouses were first built in Britain, they were financed by tolls on ships when they arrived in port, not out of general taxation. This mechanism works because ship-owners unwilling to pay for the benefits yielded by the lighthouse are excluded from using a complementary service (the port) even if they cannot be excluded from using the services of the lighthouse. A modern equivalent to this might be to finance a sector-specific measurement activity from a general levy on members of a specific trade association. While those in the industry unwilling to contribute in this way could not perhaps be excluded from use of the new measurement approach, nevertheless they could be excluded from the trade association - and it is this fear which persuades them to pay up.

Indubitably however, it can be a costly business to track down all beneficiaries from spillovers and charge them for the benefits they receive. Sometimes the benefits of doing this justify the costs; often they do not. My view on the Coaseian argument is this. The argument is correct in a world of perfect information and zero transaction costs. While there are indubitably some schemes for internalising some externalities in real worlds, there are in practice still - and always will be - a very large number of externalities that evade any levy of this sort.

Figure 20 attempts to illustrate why it may sometimes be easy to track down beneficiaries from spillovers, but sometimes may not. Suppose that a project to create a new measurement method will benefit those who seek to introduce a particular characteristic in their product or service. And suppose that amongst a population of companies, about a third would find it helpful to use this characteristic. Suppose also that these companies can be represented in a two dimensional map. The axes of this map could represent geographical space, or a more subtle competitive space. But assume at any rate that proximity in this map implies corporate proximity. So for example, all the members of a particular trade association would be clustered together in a particular part of the map.

Figure 20 represents the results of two simulations from a model of diffusion across this population of companies. In this figure, companies that use the characteristic (and hence the measurement activity) are shown in yellow (pale), while those who do not are shown in blue (dark). In the top part of Figure 20, diffusion essentially follows an *epidemic* [68] process, where companies are very likely to adopt characteristics and processes that are used by their neighbours. As a result, use is clustered into contiguous or coherent blocks. In the lower part of Figure 20 by contrast, diffusion is essentially determined by a *probit* [69] (or firm-specific) diffusion process. Here firms are less concerned by the behaviour of their neighbours, but more by the benefits they themselves would enjoy by adopting a new characteristic. As a result, use is not clustered, but instead is spread in a patchwork fashion across the whole population.

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[68] An *epidemic* model of diffusion is one in which the spread in use of a new product or technology is rather like the spread of an infectious disease or virus – hence the word, epidemic. In this context, the rate of diffusion depends on word of mouth communication between adjacent customers.

[69] A *probit* model of diffusion is one in which the rate of diffusion depends on factors such as the growth in income of customers or the reduction in the price of the product, and not on the word-of-mouth factors captured in the epidemic model.

Consider the task faced by those who seek to levy charges on those beneficiaries to a spillover, and hence internalise the spillover. If he faces a map as in the *top half* of the diagram, he has a relatively easy task to locate beneficiaries. They are almost all in contiguous block, and some at least may belong to the same trade association. So it looks as though it may be relatively easy to finance this activity by *club* subscriptions.[70] There is still the task of designing a mechanism that excludes these beneficiaries from some related benefit if they do not pay for that. But at least the task of identifying and negotiation with the beneficiaries is fairly straightforward.

Consider, by contrast, the task facing him if he has a map as shown in the lower half of Figure 20. Here it is a very hard task just to locate the beneficiaries, let alone to survey them. In such a dispersed collection of companies, it is unlikely that many belong to the same trade association. In such a setting, the inclination would be to give up and accept that this is close to being a pure public good, and that the Coaseian solution is denied by sheer transaction costs.

This example is simplistic, but it demonstrates two important points:

- First, that the extent to which spillovers can be internalised rather than leak out as externalities depends on the spatial distribution of the beneficiaries - where we use the term “spatial” in the broadest socio-economic sense, and not just in a geographical sense.

- Second, that just as the spatial pattern of diffusion of use of a new measurement technology depends on the precise character of the diffusion process, so also does the achievable rate of internalisation of spillovers. In this simple example, it appears that *epidemic* diffusion (where there is much higher probability of contagion from neighbouring companies) leads to a much higher achievable rate of internalisation than *probit* diffusion. However, it would be unsafe to generalise from this simple example, and these issues need further careful attention.

At any rate, these observations offer an interesting angle on how we can assess the importance of externalities for NMS priority-setting. Externalities may be of least concern in stable environments, where the most likely group to use the new measurement approach are spatially contiguous, and indeed where there are very few beneficiaries from other sectors or regions. In short, externalities may be of least significance where beneficiaries are distributed as in the top half of Figure 20 - because there it is possible to achieve very high rates of internalisation.

By contrast, externalities are clearly important in contexts where the beneficiaries are not a tight-knit socio-economic group, where *de novo* entry and cross-entry are important, and where indeed the benefits from a particular measurement project spread across a number of sectors. In this case, we have a pattern of externalities where beneficiaries are widely dispersed, as in the lower half of Figure 20.

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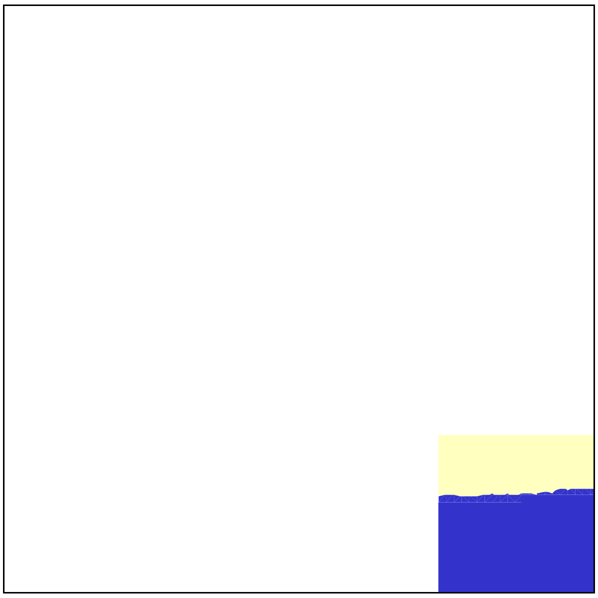
[70] Where we use the term “club” in the local public-good sense employed by Tiebout (1956) and Buchanan (1965).

Figure 20
Diffusion of Measurement Usage and Scope for Internalization

1. Diffusion to Coherent Communities



2. Diffusion to Dispersed Communities

Source: Swann (1999)

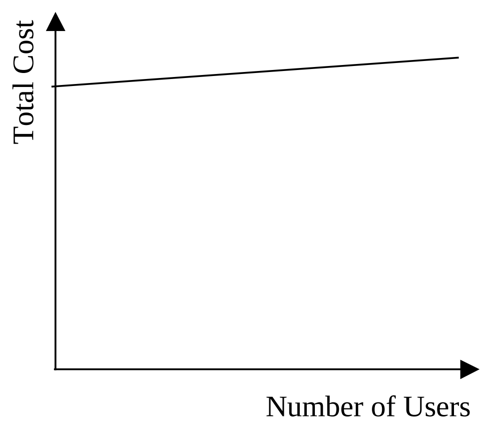
Where would this second pattern be most common? Certainly, where (in contrast to Jaffe *et al*'s research summarised in Part I) diffusion is not mediated by socio-economic proximity, and where many firms are innovators in the sense used by Koestler (1969) and Simon (1985) - that is, they bring together insights from diverse knowledge bases. This would be relevant where the mass *broadcasting* media play an important role in diffusion - so that diffusion can spread across the competitive space with ease.[71] To the extent that those who make use of new characteristics, and the measurement methodologies that support these, are Koestler/Simon innovators, then they will be very dispersed in spatial terms - and hence we can expect a very low rate of internalisation. In short, the world facing NMS is becoming more like the lower half of Figure 20, and less like the top half. So we can expect that NMS will have more and more work to do.

We conclude this section by noting an implication of the above that may seem surprising to some. "Club" solutions presume stability and familiarity. "Club" solutions, moreover, are only sustainable if they do not promote a pattern of measurement usage that disrupts this stability and familiarity. In contrast, publicly funded measurement systems encourage the sorts of innovation by outsiders that disrupts this stability and familiarity. Those who do not do well on new characteristics will not invest to create relevant measurement methodologies. Measurement "clubs" may be captured by incumbents, who could resist new product dimensions that threaten their competitive position. So a public measurement infrastructure is necessary for the most radical innovative advance.

11.4 Increasing Returns/ Economies of Scale

As discussed in Section 1, metrological research has large fixed costs, but its results can be disseminated (at least in some form) quite widely at relatively low marginal cost. The relevant graph from Figure 2 is this:

Figure 21
Cost of Dissemination of Results from Metrology



[71] An *important* distinction arises between diffusion driven by broadcasting (i.e. one-way) and diffusion driven by *communication* (two way).

This illustrates the public good (and natural monopoly) character of metrology. Once funded by one public agency, the results can be disseminated to a wide community of users at low cost. By contrast, it would be grossly inefficient for several different companies to fund independent metrology programmes – and indeed, given the fixed costs involved only a few companies would be able to fund such programmes.

In short, it is clear that the increasing returns (or economies of scale) argument is highly relevant to the case for public policy towards metrology.

11.5 Other Arguments for Public Provision

While much of the argument for public provision of metrology rests on externalities and increasing returns (or economies of scale), there are at least three other arguments that are used, which need to be noted here.

First, many would agree with Tassey (1982b) that the measurement infrastructure is most useful when used by all. As discussed in Section 5.1, this means that use of the measurement infrastructure is subject to network effects. Network effects are typically of two types. *Direct* network effects arise when network members benefit directly from the inclusion of *specific* other members in the network. *Indirect* network effects arise when network members benefit from the supporting products and services that tend to cluster around a well-used network. Direct network effects can sometimes grow without limit as the network expands, while indirect network effects tend to reach an upper limit. This suggests that policy interventions are most relevant where network effects are direct rather than indirect. With some other forms of infrastructure, such as roads, heavy use of the roads by many others causes congestion and that reduces the quality of what any one user can derive from the infrastructure. But that is rarely the case with the metrology infrastructure. Rather, in this case the quality obtained from using the infrastructure increases as the number of users increases. Tassey has developed this infrastructure argument in careful detail over several publications – see Section 5.1 – and the argument for treating this infrastructure as a public good rests on externalities and increasing returns (or economies of scale).

Second, the measurement infrastructure will only have the beneficent effects described in Sections 6-9 if it is ‘open’ to all prospective users, so that they can use it for its own purposes. If, by contrast, parts of the measurement infrastructure are ‘closed’, except to privileged and proprietary users, then the effects described will only be available to some. In the context of standards, we have seen ‘closed’ standards, useful as they may be in some contexts, do not perform all the essential functions of a standard. In particular, ‘closed’ standards do not offer a ‘level playing field’ for all competitors in the way that an ‘open’ standard can do. In the context of metrology and measurement, as discussed earlier in the report, producers with proprietary rights to a particular measurement technique are more likely to make measurements available to their customers if those measurements show them (the producers) in a good light. But if the measurements show them in a bad light, then they may simply not make them available. This is the ‘unsatisfied customer demand’ for measurements described in Figure 5 (Section 1.2) and closed measurements contribute to asymmetric information.

Third, a powerful argument for public control of weights and measures (with an impressive historical pedigree, as described in Section 2) is that society and the economy has a powerful need for impartiality and integrity in measures. Individual traders face considerable temptation to use "guile in weight or measure" (Section 2.1) and for that reason, the integrity of measurement (and measurement instruments) needs to be ensured by the state.

12. Priorities for Public Funding

One general principle seems clear. Priorities for public funding would be those aspects of metrology and measurement that show the greatest 'public good' character. Thus, referring back to the three categories described in Section 1:

i) Metrology and research in measurement: basic research, refining state of the art measurement and discovery of novel reference materials
ii) Development of measurement tools and infrastructure to carry out measurement, including: method evaluation and development, proficiency schemes and the production and certification of reference materials
iii) The day-to-day use of tools and techniques for real-world measurement

There is general agreement that (i) shows the most obvious public good properties and is most susceptible to under-provision. Some of (ii) may show public good properties but not all. By contrast, (iii) are not public goods in character and can safely be left to the market.

But going beyond that, it is much harder to generalise. Swann (2003) describes a possible framework for setting priorities in NMS programmes where the benefits from each programme are split into:

- Producer benefits
- Consumer benefits
- Externalities

We shall first (12.1) summarise that framework, then (12.2) ask whether the measurement of externalities is the right route to pursue, and if not (12.3) what other alternatives are available.

12.1 A Possible Framework: Producer, Consumer, Externalities

As noted in Section 5 above, Swann (2003) [72] identified a list of 19 mechanisms by which measurement can deliver economic returns. These are listed in Table 4 overleaf. That list is not exhaustive. For example, it does not fully capture the environmental benefits or health and safety benefits that can flow from advances in measurement. Equally, the various mechanisms described are not all independent of each other. Very often, different mechanisms will be found working side by side, and sometimes indeed one mechanism more-or-less entails another. However, this list is detailed enough for many purposes.

Swann (2003) then develops a *general-purpose micro model* to assess the effects of measurement activities. It is called a *micro model* because it analyses the effects of measurement activities at the most disaggregated level - i.e. the effects on individual companies, consumers and third parties. It is *general purpose* because it can in principle be adapted to capture the effects of any of the mechanisms identified in Table 4.

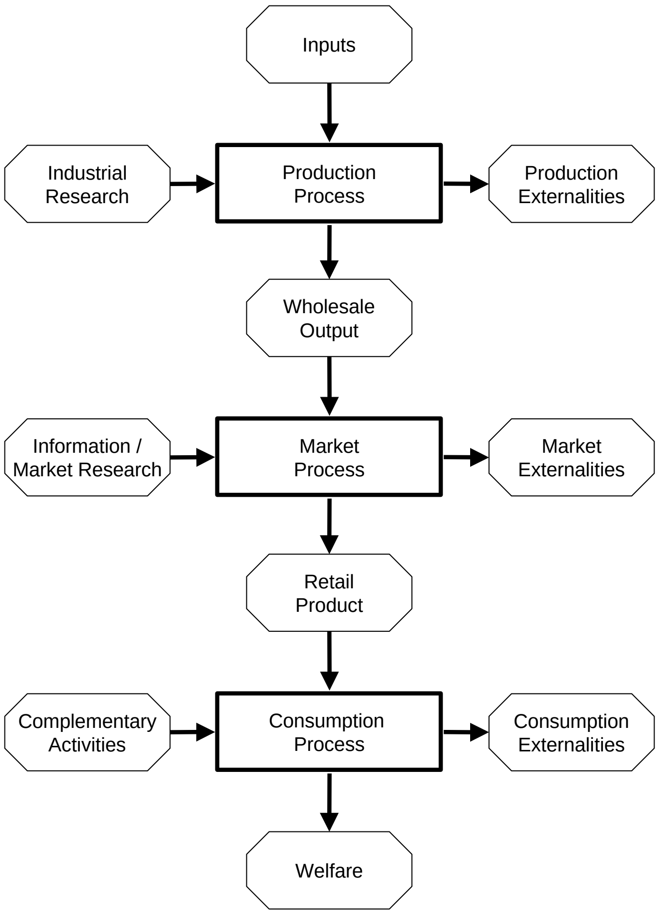
[72] This paper, together with that by Temple (2003) was part of a project to redesign the earlier MMI model developed by Klein *et al* (1996) and Bowns *et al* (2003)

Table 4
Mechanisms that Deliver Economic Returns

	Mechanism	**Description**
1	Better Decisions	Statistical hypothesis testing recognises Type I and Type II errors. Improved measurement can reduce the probabilities of Type I and/or Type II errors.
2	Better Standards and Use of Standards	Better measurement can help to achieve faster standards development, and better quality standards.
3	Common Pools For Product Innovation	Measurement underpins the use of novel product characteristics for competitive advantage. An open measurement system can help to create a common pool of potential product innovations.
4	Comparability Of Measurements Facilitates Trade	The growth of trade requires the reduction of transaction costs, and an essential part of that is the emergence of common standards and measurements.
5	Division Of Labour - Interchangeable Parts	Accurate and comparable measurement enables further division of labour, and greater use of interchangeable parts.
6	Dosage Issues	For a wide variety of products, precise measurements of product characteristics (or doses) are essential for efficacy and safety.
7	Easier To Demonstrate Quality And Safety	Accurate measurement of product characteristics makes it easier to demonstrate quality and safety, and hence to sustain a price premium for superior products.
8	Enabling A New Market	The creation of new forms of market is as important as other types of innovation. Measurement also plays an important role in the reduction of "market failure".
9	Enabling A New Process	Measurement is often essential to the control of complex systems that enhance productivity. Better measurement can increased process efficiency, and help to achieve energy savings.
10	Enabling A New Product	Measurability of product characteristics promotes product innovation, by making it easier to demonstrate quality, and hence sustaining a price premium for quality.
11	Improved Product Quality	Improved measurement enables quality control, allows the sorting of products by quality, enables more accurate doses, tighter tolerances and higher purity.
12	Increased Productivity / Process Efficiency	Better measurement can enable the use of new processes and/or increased process efficiency. It enables the implementation of new complex systems that enhance productivity.
13	Patent Protection	Measurement has an important role in the patenting process, which in turn enhances the profitability of the patent-owner.
14	Quality Control	Improved measurement enables quality control.
15	Reduced Costs of Meeting Regulations	Improved measurement can make it easier and cheaper to ensure regulatory compliance, and can thereby lead to a lower regulatory burden.
16	Reduced Damage from Externalities	Improved measurement can make it easier to achieve more demanding environmental regulations, and hence reduce the environmental damage from externalities.
17	Reduced Transaction Costs	The comparability and traceability of measurement reduces some of the risks in trading, and hence reduces transaction costs.
18	Shorter Times To Market	Better measurement can help companies bring products to market in a shorter time-span.
19	Testing That Equipment Is Working Properly	Measurement obviously plays a key role in testing equipment and ensuring it works properly.

To give the reader an idea of how this model works, we shall focus on one specific example that can be described by a simple flowchart (see below).

Figure 22
Example of a Flowchart to Identify Measurement Impact



Source: Swann (2003)

This flowchart pictures in a very simple way the micro-economic process linking production to consumption, through a market. There are three main stages in this process. First comes the production process, combing inputs and using industrial research to create (wholesale) outputs. This production process may also create pollution or other production externalities - and for simplicity of exposition we shall assume here that such externalities are negative (though that is not an essential assumption). Second comes the market process, which uses information and market research to take products from wholesale into retail markets. This market process may also create externalities for third parties - such as the benefits that third party consumers and producers may enjoy when one particular company creates a market. Third, comes the consumption process (or more generally we can replace the word "consumption" by "use"). Here, consumers combine retail products and other services with complementary activities to generate welfare. (Or more generally, customers combine products and activities to create some broader concept of welfare or performance). The consumption / use process can have externalities for third parties - such as the pollution consumers cause when they drive their cars, or the noise-pollution they create when they play the radio too loud.

This flowchart is obviously a simplified version of the economic process by which we eventually turn raw materials and primary inputs into welfare. However it is broad enough for our present purposes.

Where does measurement fit into this picture? The short answer is *anywhere*! As we have designed the model, measurement can improve the operation of any of the linkages in the diagram. Thus, for example, improved measurement can:

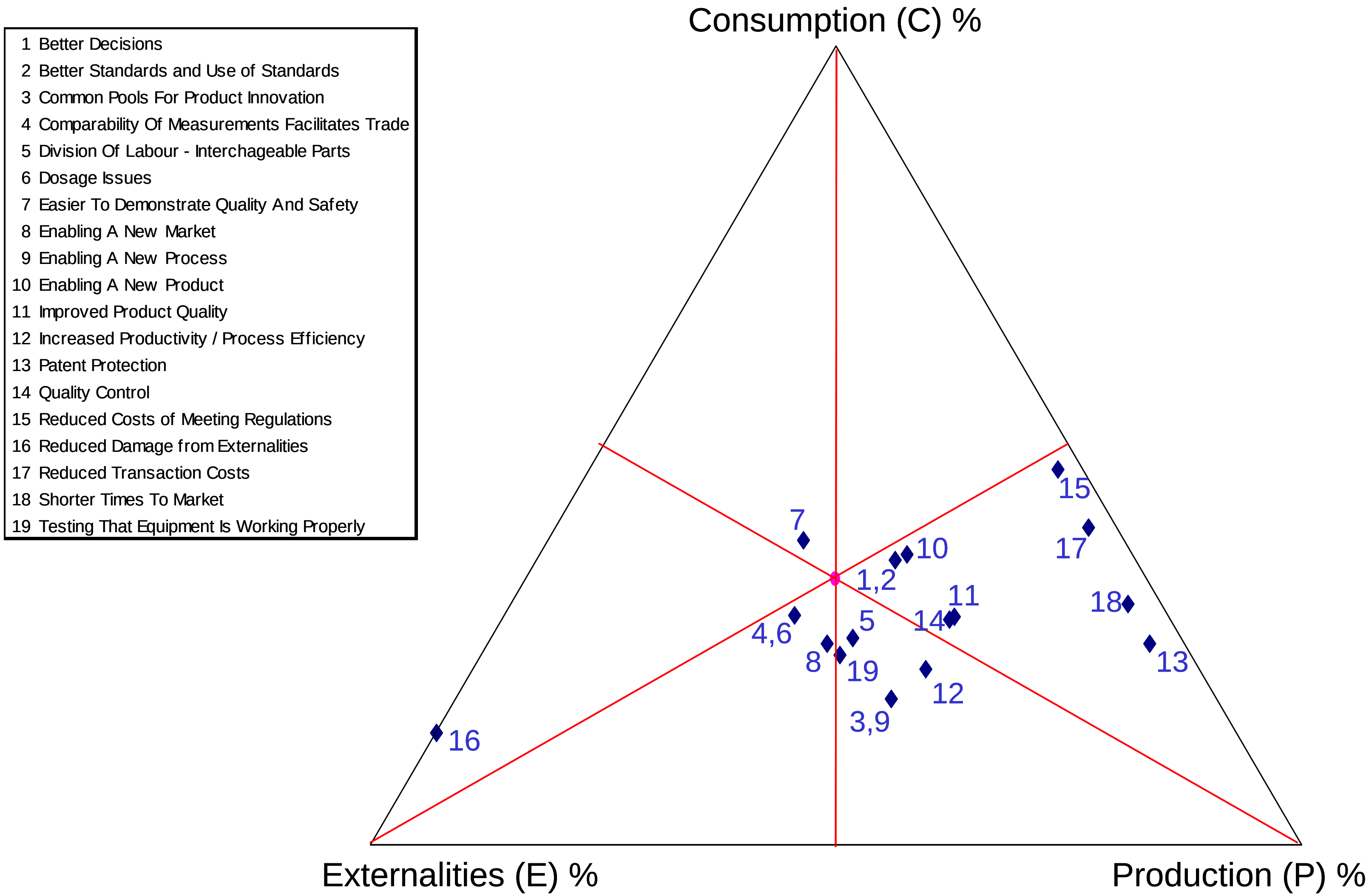
- enhance the production process turning inputs into outputs
- reduce the externalities from the production process
- reduce the costs involved in turning production outputs into marketable products
- improve consumer welfare from any given purchase of retail products

Swann (2003) shows that all of the mechanisms identified in Table 3 can be described within this flowchart. Swann (2003) also shows how the flowchart can be turned into a workable economic model by assuming that each stage in the process (production, market, consumption) can be summarised by *two* Cobb-Douglas[73] production functions. Starting with the production process, the first function describes how production combines inputs and research to create wholesale outputs. The second function describes how production combines inputs and research to create externalities. Turning next to the market process, the first function describes how the market process combines wholesale products and information/market research to create retail outputs. The second function describes how the market process combines wholesale products and information/market research to create spillovers. Finally, turning to the consumption process, the first function describes how consumption combines retail products and complementary activities to create welfare. The second function describes how consumption combines retail products and complementary activities to create externalities. In short, six functions describe all the linkages in the above flowchart.

If certain computations are feasible for each programme – and it is quite a big if, as the sorts of computations made in NIST (2003, n.d.) measurement studies are costly – then it is possible to compare different programmes in a triangular diagram, as shown in Figure 23, overleaf. This shows the percentage split of benefits between the three above categories: Producer benefits, consumer benefits and externalities.

[73] The Cobb-Douglas form is especially convenient for this purpose, and is widely used to provide a simple but powerful parameterisation for many economic models of production.

Figure 23
Division of Benefits between Producers, Consumers and Externalities



King and Nettleton (2006) have applied this framework to some NPL metrology programmes using a simpler list of benefit mechanisms. This yields a triangular plot (Figure 24) where the points are fairly closely arrayed along a line where:

$$\frac{\text{Producer Benefit}}{\text{Consumer Benefit}} \approx K > 1$$

where K is a constant. In short, while the level of externalities may vary quite a lot between these different metrology programmes, the ratio of producer benefits to consumer benefits is roughly constant. Why should that be? For the most part it arises because the ratio of producer benefits to consumer benefits is roughly constant in the four elementary mechanisms considered by King and Nettleton (2006) and hence any programmes which work through a composite of these mechanisms will also show that regularity.

By contrast, the 19 mechanisms considered by Swann (2003), and described in Table 3 above, do not show that regularity – see Figure 23 – though typically it is still the case that K > 1.

The extent to which a project is a priority for public funding will depend on the share of benefits accruing as externalities and (to a lesser extent) to consumers. The under-provision problem will typically be most serious for projects for which this combined percentage is largest. In terms of Figure 23 above and Figure 24 below, the priority projects for public funding would be those located to the 'west' and 'north' in the triangle.

12.2 Is the Measurement of Externalities the Right Target?

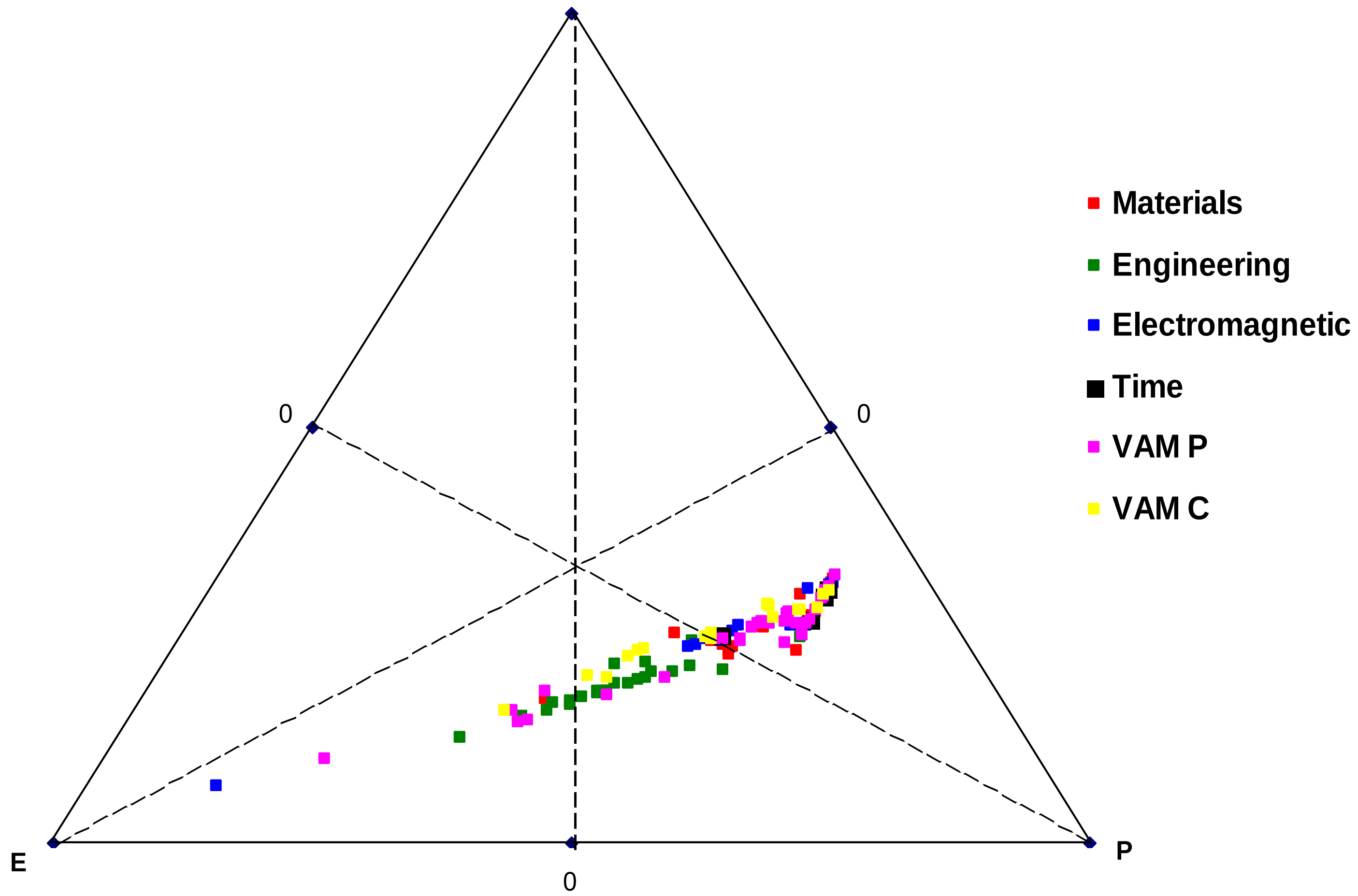
The externality framework is very flexible and can be adapted to almost any project of this sort. But the problem with it is that it can be very costly to research and measure externalities. Almost any project has externalities, and they occur everywhere, but the theory of externalities gives us very little guidance on where they are to be found.[74]

Swann (1999) set out a detailed strategy for seeking out externalities in this context. This includes some guidance on where we start looking, and some observations on a how to identify and Measure externalities. However, the resources needed to apply these methods seem to be beyond the resources that NMS (at present) wishes to invest in measuring the economic benefits of metrology.

Why is it so difficult to trace and measure externalities? In an often-cited paper on the search for spillovers, one of the great applied econometricians, Griliches (1992) concluded that spillovers were often very important, but were very hard to quantify.

[74] Compare Mary Douglas, quoted in Gorman (1976): "Utility theory is empty so we can fill it". We could adapt this saying to the present context as follows: "The theory of externalities is empty so we can fill it."

Figure 24
King and Nettleton's Illustration of a 'Swann Triangle'



Source: King and Nettleton (2006)

It is worth reflecting on this observation. For simplicity, take the case of positive spillovers - that is, where one person's investment creates benefits for others who are not party to the investment. An economist in the Chicago (i.e. ultra free-market) tradition might argue as follows:

> "There is a strong incentive for business-people to internalise positive spillovers. Either it is easy to do this, or it is difficult. If it is easy, then we can rely on business people to internalise. Then when this has been done, there will be no externalities left. If it is difficult, because business-people can't track down all the externalities, then how can the researcher expect to do so? In short, the conclusion would be that externalities are either unimportant or impossible to identify."

Actually, this answer is incomplete because it fails to make an important distinction between: (a) the ability to track down where the spillovers are accruing; and (b) the ability to contrive a contractual arrangement to internalise these spillovers. If business-people are to internalise spillovers they must have (a) *and* (b). The researcher, by contrast, only needs to have (a).

A simple example will illustrate the point. Suppose that a developer buys a derelict house in an otherwise well-to-do street, and improves that house. It is likely that there will be positive externalities from this to immediate neighbours, and perhaps all the way along the street. The developer knows where the beneficiaries are. He can knock on their doors, indeed! But it is rare to see such developers contract with neighbours to internalise these externalities. The issue is not one of locating the beneficiaries. Nor is it because of the impossibility of measurement. For here, a surveyor could give a good idea of the amenity value of having a house in good condition next door, rather than a derelict house.[75] No, the difficulty arises because it is difficult for the developer to find any way to make the neighbours pay towards this externally, for if they believe the developer will go ahead anyway, they have no incentive to reveal the value of their amenity windfall.

Our perspective, hence, is that the pessimistic conclusion of the (hypothetical) Chicago economist overstates the case. It *is* possible for important externalities to exist *and* for the researcher to track them down.

12.3 Alternative Approaches

While the triangular plots shown above seems an appealing way to assess priorities, it is difficult and time consuming. For this reason, a more practical approach to identifying priorities for NMS programmes may be different. Rather than attempt to track down and measure externalities in detail, it is better to identify certain criteria which point towards public funding rather than private (or club) funding.

These could include the following criteria, which overlap with each other to some extent.

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[75] Or an economist with sufficient data on house prices and characteristics could use "hedonic" regression analysis to estimate a shadow price for this amenity. A lot of applied econometric work in environmental economics has taken such an approach.

Cases where the risks from ‘closed’ metrology are serious

Here the discussion of Section 11.5 is relevant. Closing parts of the metrology infrastructure can deny the economy from many of the benefits described in Sections 7 (innovation), 8 (reduced transaction costs) and 9 (benefits to other users). The consequences for the effects in Section 6 (productivity within the business) may be less damaging.

Cases where benefits are very diffuse across industrial sectors

Here the discussion of Section 11.3 is relevant. There we explored the circumstances in which internalisation would be relatively easy and the contrasting circumstances in which internalisation is difficult.

Cases where the fixed costs of metrology are especially high

Here the discussion of Sections 1.1 and 11.4 are relevant. Section 1.1 argued that the fixed cost argument is most relevant to metrology (as research), that it may be relevant to some areas of instrument development, but rarely applied to the practical day-to-day use of measurement within the business.

Cases where the benefits are spread over *many* categories of users

Here the discussion of Section 9 is relevant. Contrary to the simple idea that measurement is used primarily by business for business, we saw in Section 9 that measurement is used by consumers, health practitioners, environmentalists, health and safety officers, educators and trainers, researchers and others.

Cases where the Network Effects from Infrastructure Use are Strongest

Again, the discussion of Section 11.5 is relevant here. These are cases where the benefits described in Sections 6 (productivity), 7 (innovation), 8 (reduced transaction costs) and 9 (benefits to other users) are stronger the more widespread is the use of the measurement infrastructure.

This is as far as we can take these criteria for now. To explore whether these criteria can be used to help set priorities for public funding of metrology will require dialogue between policy makers, the author and other experts on the economics of measurement.

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